Bendix Navigation & Control Division

REVISED
FINAL REPORT

APOLLO
TELESCOPE
MOUNT (ATM)
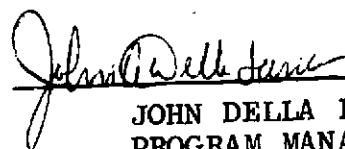GIMBALLED
STAR TRACKER

PREPARED
PER THE
REQUIREMENTS
OF
NAS-30105

1974

PREPARED BY
THE BENDIX
CORPORATION

GUIDANCE
SYSTEMS
DIVISION

TETERBORO,
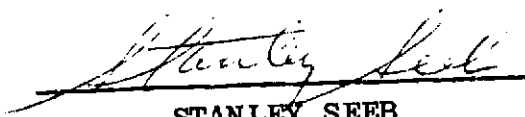NEW JERSEY

PREPARED BY:
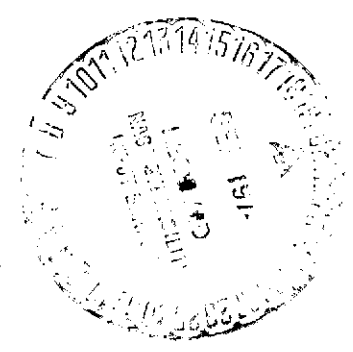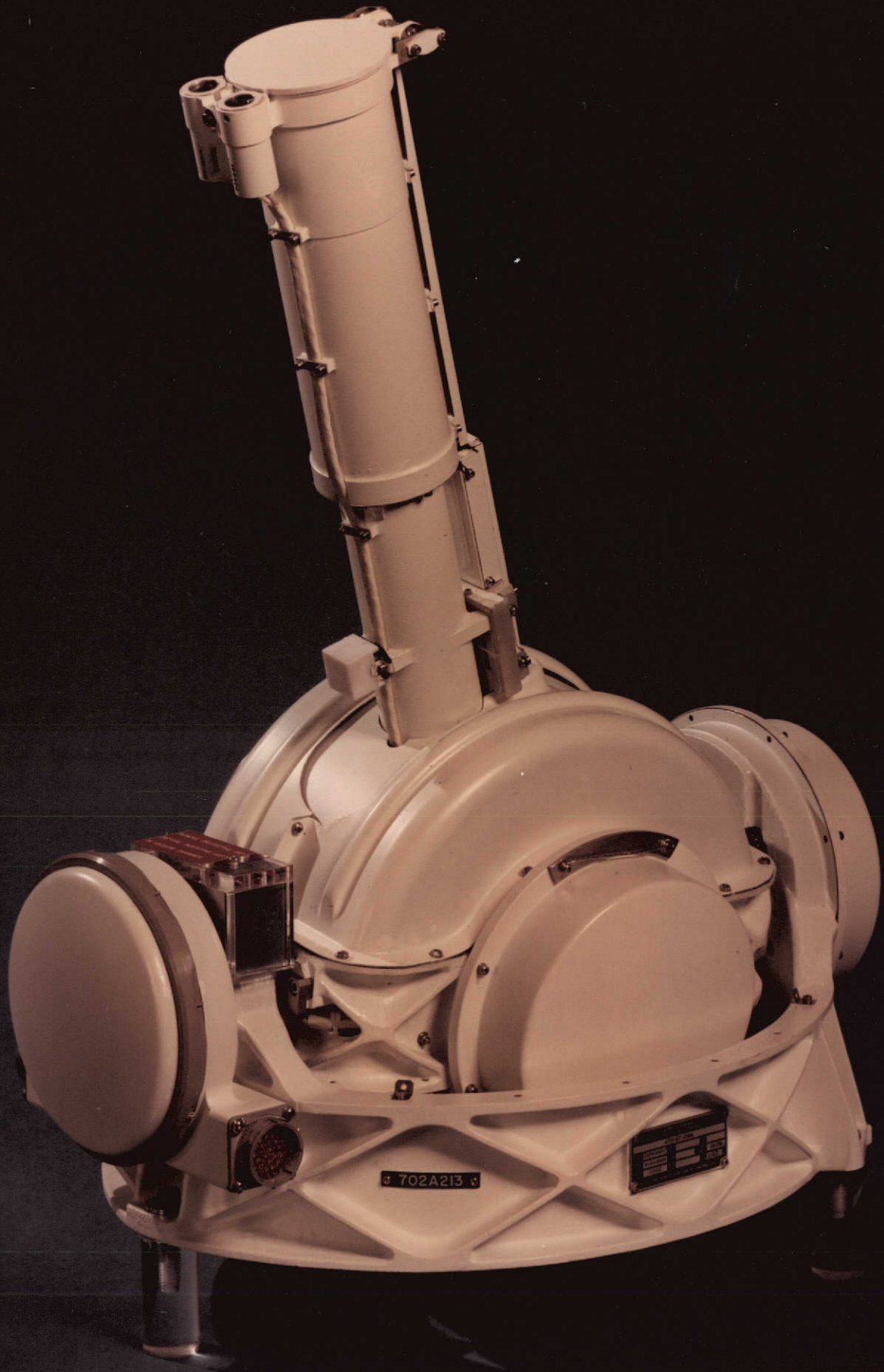
JOHN DELLA LANA
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APPROVED BY:

STANLEY SEEB
SUPERVISOR-ELECTRO-OPTICS SYSTEMS

FOREWORD

During a period from September 1968 to February 1974 the Guidance Systems Division of the Bendix Corporation designed, built and delivered to Marshall Space Flight Center, six gimballed star trackers for the Apollo Telescope Mount of Skylab. The flight unit performed successfully on Skylabs I, II and III, receiving a total accumulated usage time of approximately 3500 hours. The tracker contributed to the mission successes by providing accurate pointing for experiments and roll references for gyro updates.

This report will describe how the tracker is used, discuss the delivered design, describe its test equipment and qualification test results and summarize its reliability characteristics.

The appendices of this report contain a brief program history and discuss design changes incorporated during the life of the program.

INDEXES BY LOOSE LEAF INDUSTRIES

SECTION 1.0

SUMMARY

1.0   ATM STAR TRACKER SYSTEM

The ATM Star Tracker designed for NASA-Marshall Space
Flight Center consists of a refractive telescope mount-
ed in a double gimbal suspension. Each gimbal is
driven by a direct drive D.C. torquer, while gimbal
rate control is provided by D.C. Tachometers. Thirty
arc second resolution optical encoders mounted on each
axis provide the angular position information necessary
to generate a roll reference for the ATM telescope.
Gimbal freedoms of $\pm$ 87° around the outer gimbal and
$\pm$ 40° around the inner gimbal are sufficient to track
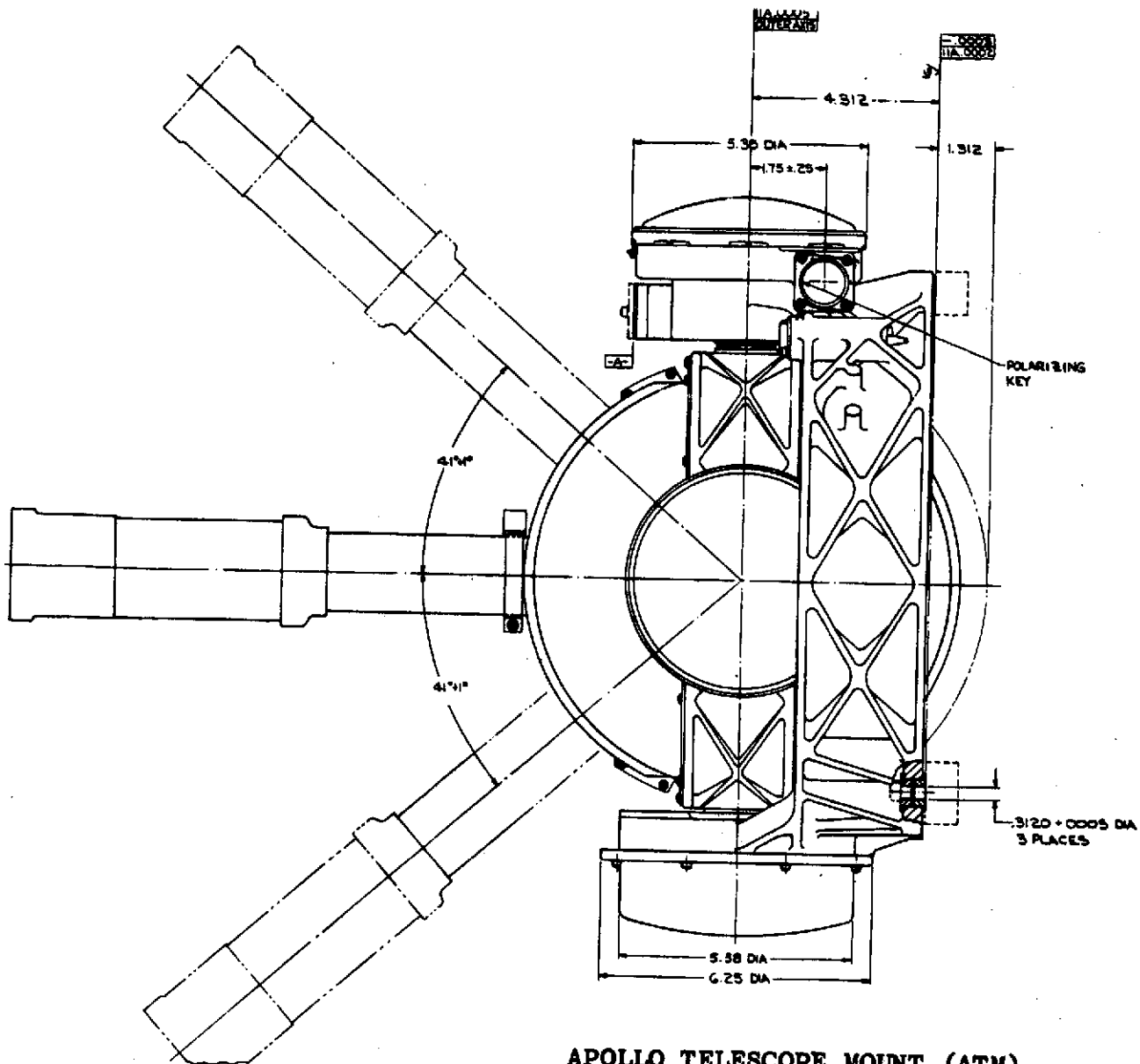Canopus, Achernar and Acrux.

The telescope has a scanned field-of-view of 1^O square
and an instantaneous field-of-view with a 10 arc minute
square. This dual field-of-view provided a large view-
ing area while having low susceptibility to background
effects. The Star Tracker automatically locks the in-
stantaneous field at the star's position within the one
degree field. The gimbals then drive the optical axis
in line with the star line. A combination sun and earth
albedo shade has been provided which will allow tracking
of stars to within 45° of the sun and 5° of the earth.

An electronics package was designed to provide power
supplies, servo amplifiers, Digital Logic Unit (DLU)
encoder processing electronics, telemetry and other
functions. Figures 1-1 and 1-2 show a photograph and

outline of the ATM Optical Mechanical Assembly (OMA).
Figure 1-3 is the outline of the Star Tracker Support
Electronics (STE).

The ATM Star Tracker is capable of three modes of opera-
tion: manual, search and track. The manual mode pro-
vides the astronaut with a remote gimbal positioning
capability. Automatically, the search mode, utilizing
the electronic digital logic unit, initially scans a small
$\pm 2^{O}$ field of view and locks onto any target star in this
field. If no target star is located in this field, it
automatically searches a larger $+ 5^{O}$ field of view about
the inner gimbal axis and $\pm 15^{O}$ about the other gimbal
axis until a target star is acquired. After the system
acquires it, it switches to the track mode which pro-
vided high accuracy tracking of the target star.

The system successfully performed on all three Skylab
missions and received an accumulated usage period of
over 3500 hours.

APOLLO TELESCOPE MOUNT (ATM)
OPTICAL MECHANICAL ASSEMBLY (OMA) OUTLINE
FOR SKYLAB
FIGURE 1-1

SUMMARY OF CHARACTERISTICS

FIELDS OF VIEW

GIMBAL	$\pm 87^{\circ}$ OG, $\pm 40^{\circ}$ IG
TELESCOPE	1° SEARCH
	10' TRACK

ACCURACY — 30 ARC SEC

TARGET STARS — CANOPUS, ACHERNAR, ACRUX (+1.2 MAG)

MAGNITUDE CAPABILITY — +2.0

OPTICS — 175mm F/6.8 (FOLDED)

DETECTOR — FW143 (ITT)

MODULATION — GIMBAL SEARCH (10°x30°): ELECTRONIC RASTER 1°x1°

CRUCIFORM TRACK

WEIGHT — 38 LBS (OMA)

POWER — 15 WATTS

ATM STAR TRACKER

SUN SENSOR

SUN SHADE

OUTER GIMBAL AXIS

EARTH ALBEDO SENSOR

OPTICAL ENCODER

TORQUER-TACH ASSEMBLY

ALIGNMENT FIXTURE PADS (3)

INNER GIMBAL AXIS

MOUNTING PADS (3)
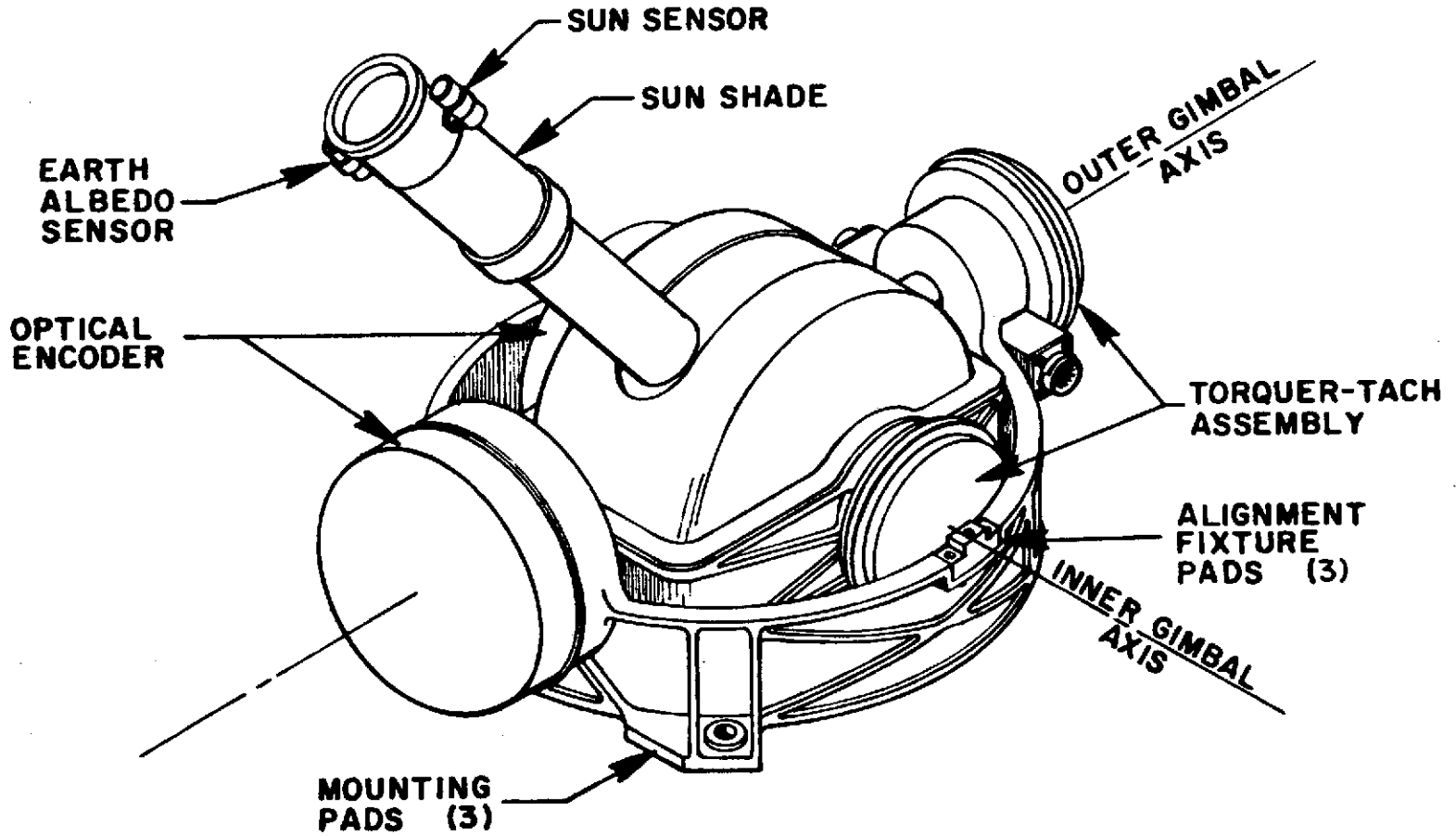
APOLLO TELESCOPE MOUNT (ATM)
OPTICAL MECHANICAL ASSEMBLY (OMA) OUTLINE
FIGURE 1-2

Bendix
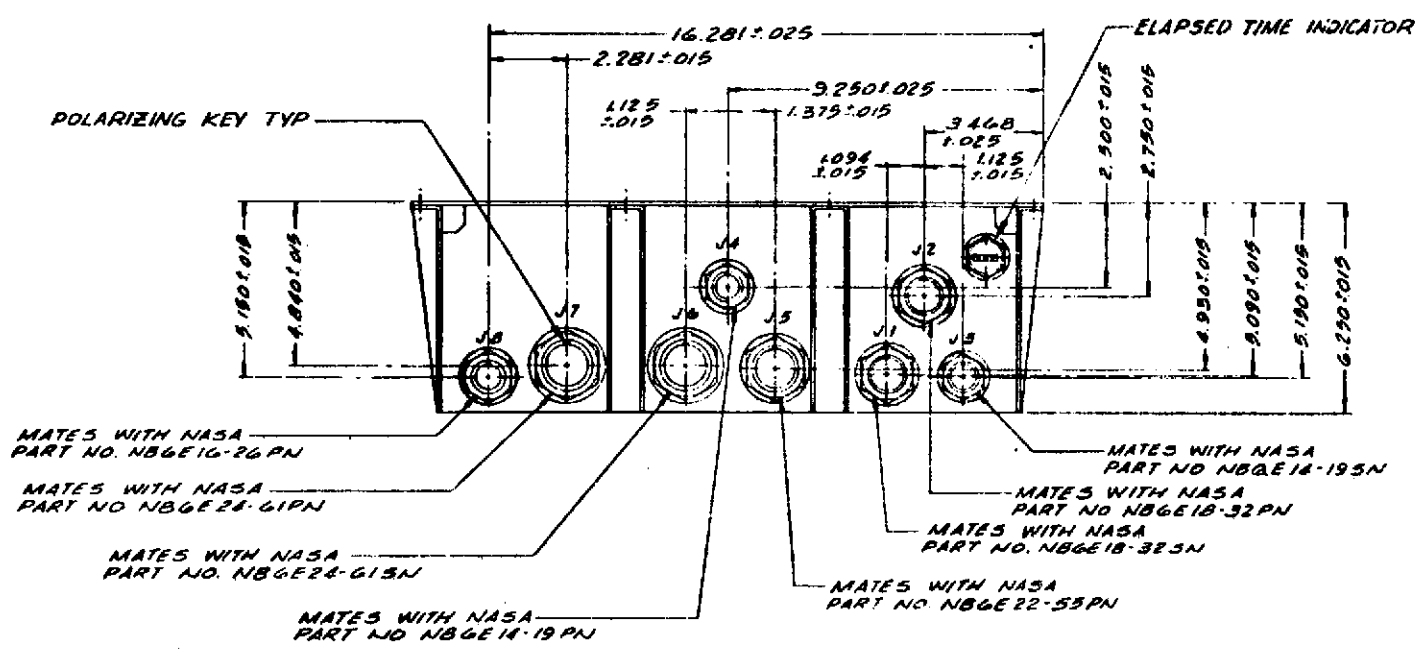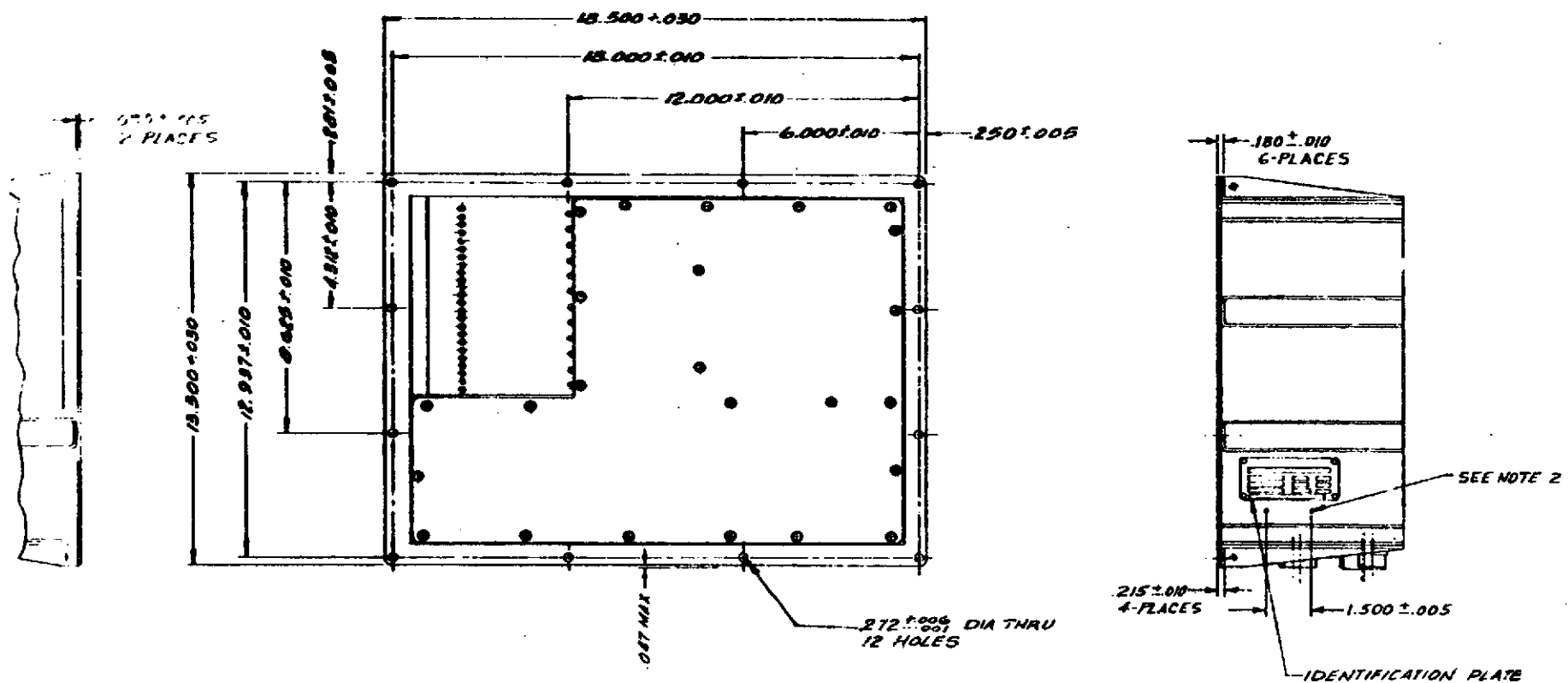
Navigation & Control Division

FIGURE 1-3

NOTES:
1 ALL EXTERIOR HOUSING SURFACES (EXCEPT MOUNTING SURFACE)
PAINTED WITH FLAT BLACK TEMPERATURE CONTROL PAINT
(CAT·A·LAC 463-3-B) PER 1854097(PS).
2 NUMBER 2-56 SCREWS PROVIDED FOR REFERNCE DESIGNATION
PLATE.

SPECIFICATION CONTROL DRAWING

ATM STARTRACKER
ELECTRONICS ASSY

SECTION 2

SECTION 2.0
STAR TRACKER DESCRIPTION

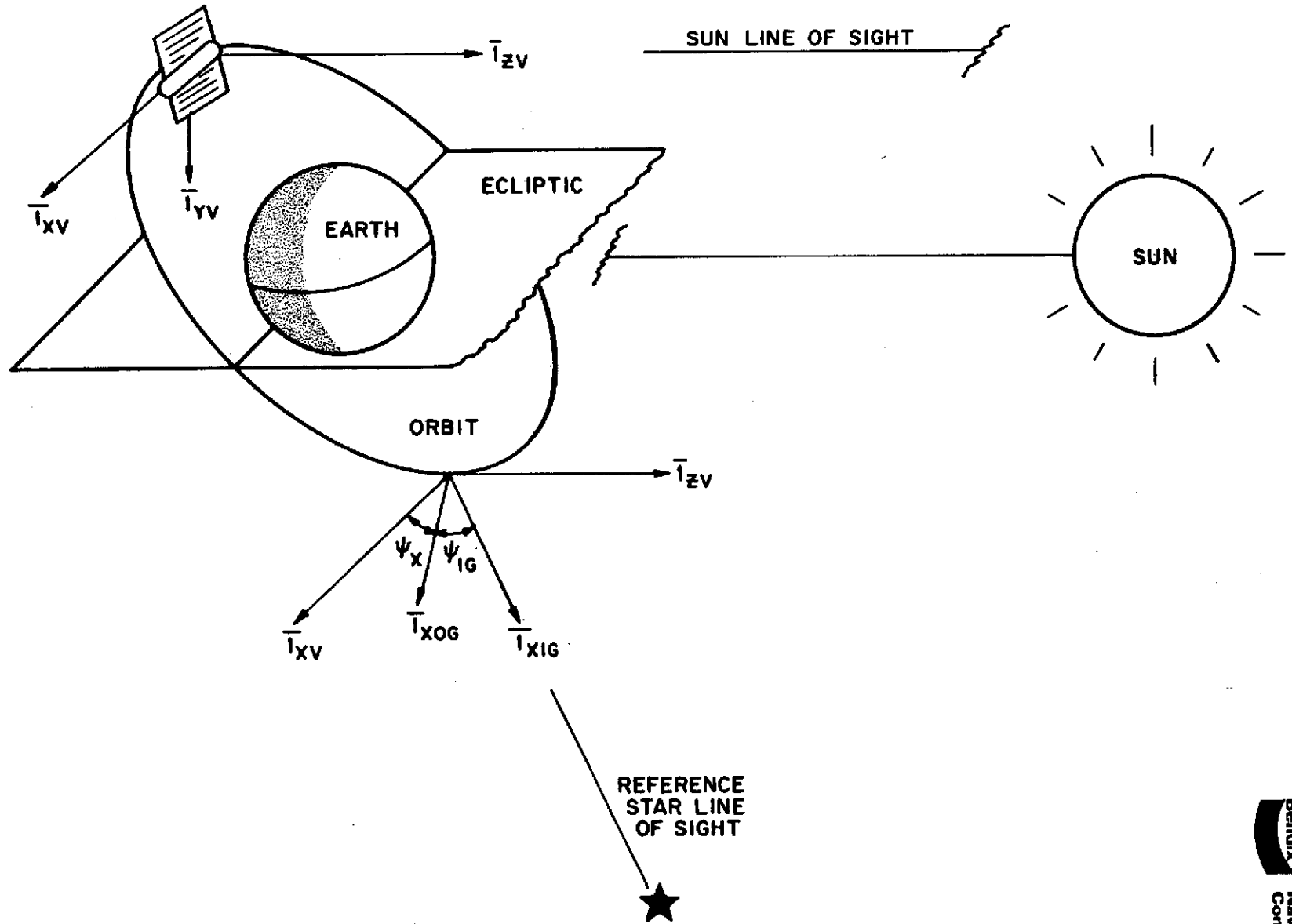2.1   SYSTEM APPLICATION AND DESCRIPTION

The ATM Star Tracker consists of a refractive tele-
scope mounted in a double gimbal suspension. Each
gimbal is driven by a direct drive DC torquer, while
gimbal rate control is provided by DC Tachometers. A
modified fifteen bit (30 arc second resolution) opti-
cal encoders mounted on each axis provide the angular
position information necessary to generate a roll
reference for the ATM telescope. Gimbal freedoms of
87° around the outer gimbal and $\pm$ 40° around the inner
gimbal are sufficient to track Canopus, Achernar, and
other guide stars.

2.1.1   System Application

The two-axis gimballed star tracker was used to serve a
dual function for the Apollo Telescope Mount (ATM)
vehicle's control and stabilization system:

(a)   A determination of the orientation of the Solar
      North Pole relative to the experiment telescope's
      reticle.

(b)   To determine the orientation of the spacecraft's
      longitudinal axis relative to the orbital plane.

Relative to (a) above, the experiment roll angle cor-
rection is calculated in an airborne digital computer
as a function of (1) the known Solar North orientation
relative to the ecliptic, (2) position of earth in the

SUN LINE OF SIGHT

$\overline{I}_{ZV}$

ECLIPTIC

EARTH

SUN

ORBIT

$\overline{I}_{XV}$

$\overline{I}_{YV}$

$\overline{I}_{ZV}$

ψ_X ψ_{IG}

$\overline{I}_{XV}$ $\overline{I}_{XOG}$ $\overline{I}_{XIG}$

REFERENCE
STAR LINE
OF SIGHT

SPACECRAFT IN ORBIT
FIGURE 2.1.1-1

solar orbit, (3) star tracker gimbal positions, (4)
right ascension and declination of the reference star,
and (5) the orientation of the experiment telescope
relative to the spacecraft. This experiment roll angle
correction is then made available for ATM display and/or
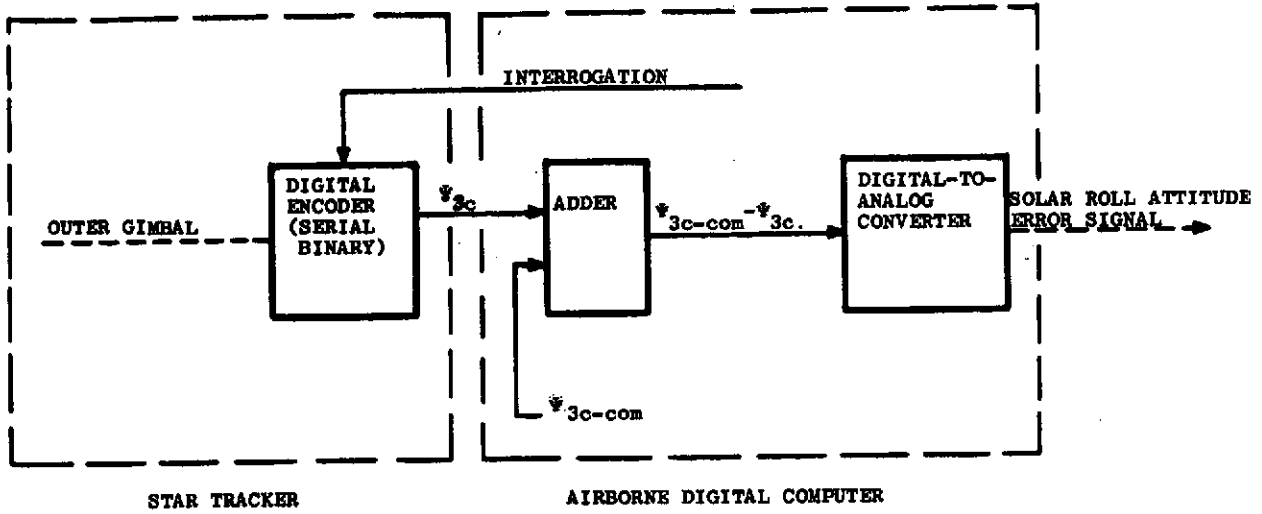telemetry for correlation with experiment data.

Relative to (b) above, the spacecraft's longitudinal
axis is defined as that coinciding with the vehicle's
minimum principlal axis of inertia. During the sun-lit
portion of the orbit, the desired orientation of the
spacecraft is along the solar roll ($\overline{I}_{zv}$) axis pointing
towards the sun and with the longitudinal ($\overline{I}_{xv}$) axis
constrained to the orbital plane. Orientation of the
$\overline{I}_{xv}$ axis in this manner thereby minimizes the magnitude
of steady gravity gradient moments on the spacecraft.

Figure 2.1.1-1 illustrates the spacecraft in orbit,
including the orientation of the vehicle's $\overline{I}_{xv}$ $\overline{I}_{yv}$
and $\overline{I}_{zv}$ axes. Also

Ψ_{3c} = rotation of the star tracker's outer
gimbal about $\overline{I}_{zv}$ or the solar roll axis.

Ψ_{1c} = rotation of the star tracker inner gimbal
to align its telescope along the line-of-
sight to the reference star.

The outer gimbal angle position is normally controlled
as shown in Figure 2.1.1-2. The Ψ_{3c} outer gimbal en-
coder signal is combined with the outer gimbal command
signal (Ψ_{3c-com}) in the digital computer. The Ψ_{3c-com} -
Ψ_{3c} signal then is used as a solar roll attitude error

INTERROGATION

| DIGITAL ENCODER (SERIAL BINARY) | | ADDER | | DIGITAL-TO-ANALOG CONVERTER |

OUTER GIMBAL

Ψ_{3c}

$\Psi_{3c-com} - \Psi_{3c}$

SOLAR ROLL ATTITUDE ERROR SIGNAL

Ψ_{3c-com}

STAR TRACKER   AIRBORNE DIGITAL COMPUTER

OUTER GIMBAL CONTROL
FIGURE 2.1.1-2

| ASTRONAUT | | HAND CONTROLLER | | OUTER GIMBAL SERVO |
| DISPLAY | | SIGNAL PROCESSER | | DIGITAL SHAFT ENCODER |

OUTER GIMBAL
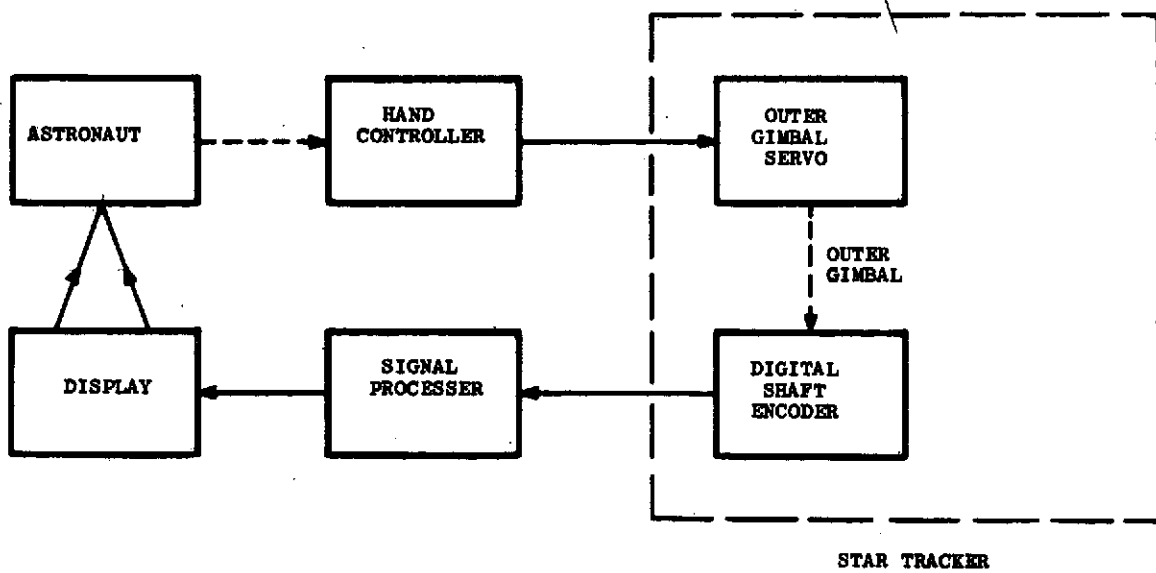
STAR TRACKER

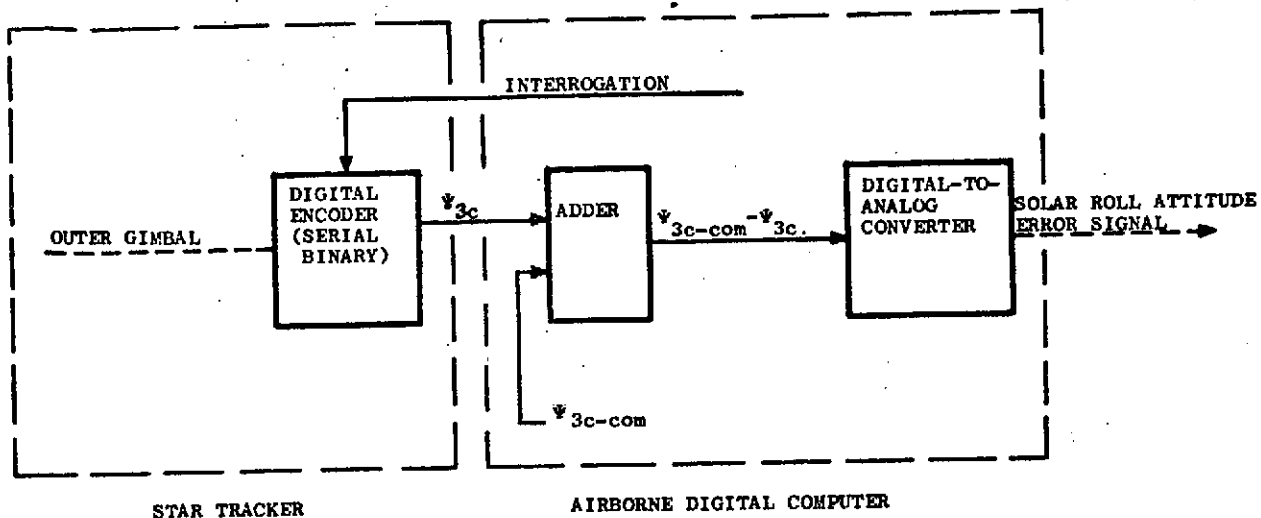INNER GIMBAL POSITIONING
FIGURE 2.1.1-3

error signal for the z_v axis of the spacecraft. The required Ψ_{3c-com} angle is determined on the ground or computed in the airborne digital computer.

For a better understanding of the star tracker's application to the ATM mission, the operation for several conditions will be discussed briefly.
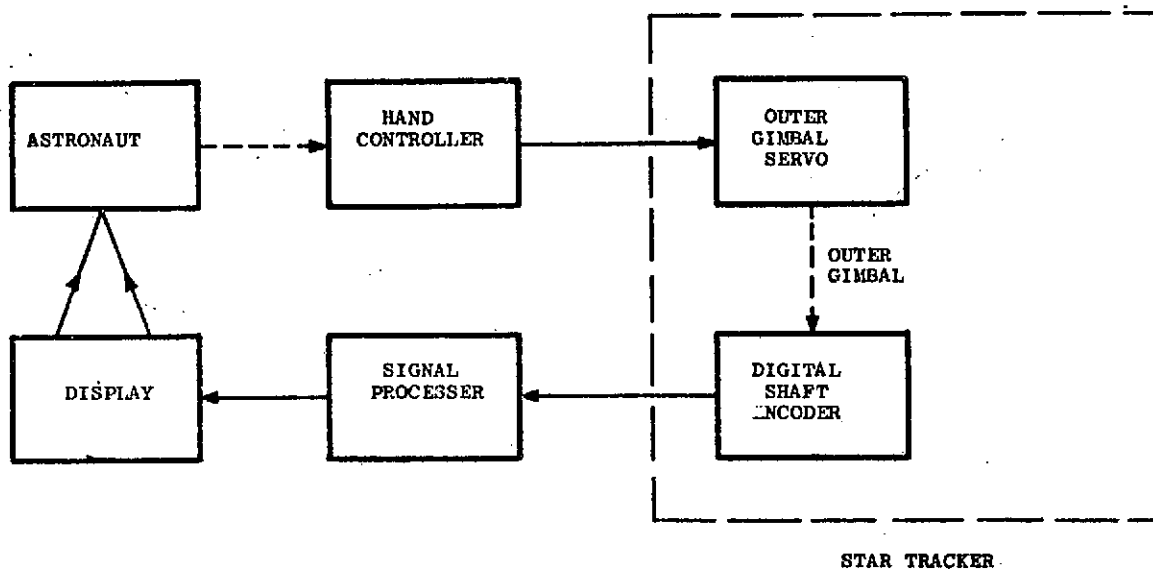
2.1.1.1   Initial Acquisition

The initial acquisition of the reference star is accomplished through the following steps:

(a)   The $\overline{I}_{zv}$ axis of the vehicle must be approximately along the solar reference line; e.g., as may be obtained with a coarse or "acquisition" sun sensor.

(b)   The astronaut then approximately aligns the longitudinal $(\overline{I}_{xv})$ axis by slewing the vehicle until this axis is within 15 degrees of the orbital plane.

(c)   The astronaut then receives the desired Ψ_{1c} and Ψ_{3c} angles from the ground control.

(d)   The astronaut may then drive the tracker's inner gimbal (Manual Mode) to match the Ψ_{1c} desired by using the hand controller until the corresponding Ψ_{1c} angle is read on the digital display. See Figure 2.1.1-3.

(e)   After "locking" the inner gimbal (Inner Gimbal Hold) the tracker's outer gimbal Ψ_{3c} is then set to the angle desired by the astronaut using the hand controller and the Ψ_{3c} digital display.

INTERROGATION

| OUTER GIMBAL | → | DIGITAL ENCODER (SERIAL BINARY) | Ψ_{3c} → | ADDER | Ψ_{3c-com} - Ψ_{3c} → | DIGITAL-TO-ANALOG CONVERTER | SOLAR ROLL ATTITUDE ERROR SIGNAL → |

Ψ_{3c-com}

STAR TRACKER   AIRBORNE DIGITAL COMPUTER

OUTER GIMBAL CONTROL

FIGURE 2.1.1-2

ASTRONAUT	→	HAND CONTROLLER	→	OUTER GIMBAL SERVO

OUTER GIMBAL

| DISPLAY | ← | SIGNAL PROCESSER | ← | DIGITAL SHAFT ENCODER |

STAR TRACKER

INNER GIMBAL POSITIONING

FIGURE 2.1.1-3

(f)   The astronaut then commands the star tracker to transfer to the Automatic Mode; more specifically, the Acquisition Search Sub-Mode.

(g)   The star tracker then goes through a dual search pattern. Initially a 4° x 4° area is searched in a short period of time and, then the full $\pm 5^O$ inner gimbal by $\pm$ 15 outer gimbal area is searched about the positions obtained in (e) above.

(h)   When the reference star is acquired, the star tracker transfers to the Track Sub-Mode.

2.1.1.2   Earth Occultation of the Reference

(i)   A star occult signal (originating from memory storage or ground telemetry) is obtained from the digital computer at a designated time before the reference star is occulted. Under this condition, the star tracker shutter is closed and both gimbals are electronically "locked" by a position loop. (Hold Mode).

(j)   At a designated time after earth occultation, a digital computer discrete commands the tracker to return to the Automatic Mode; the shutter is opened and the Hold Mode removed.

(k)   If the star tracker is then aligned within $\pm$ 30 arc min. from the reference star line-of-sight (as detected by telescope electronics), the tracker reverts back to the Track Sub-Mode.
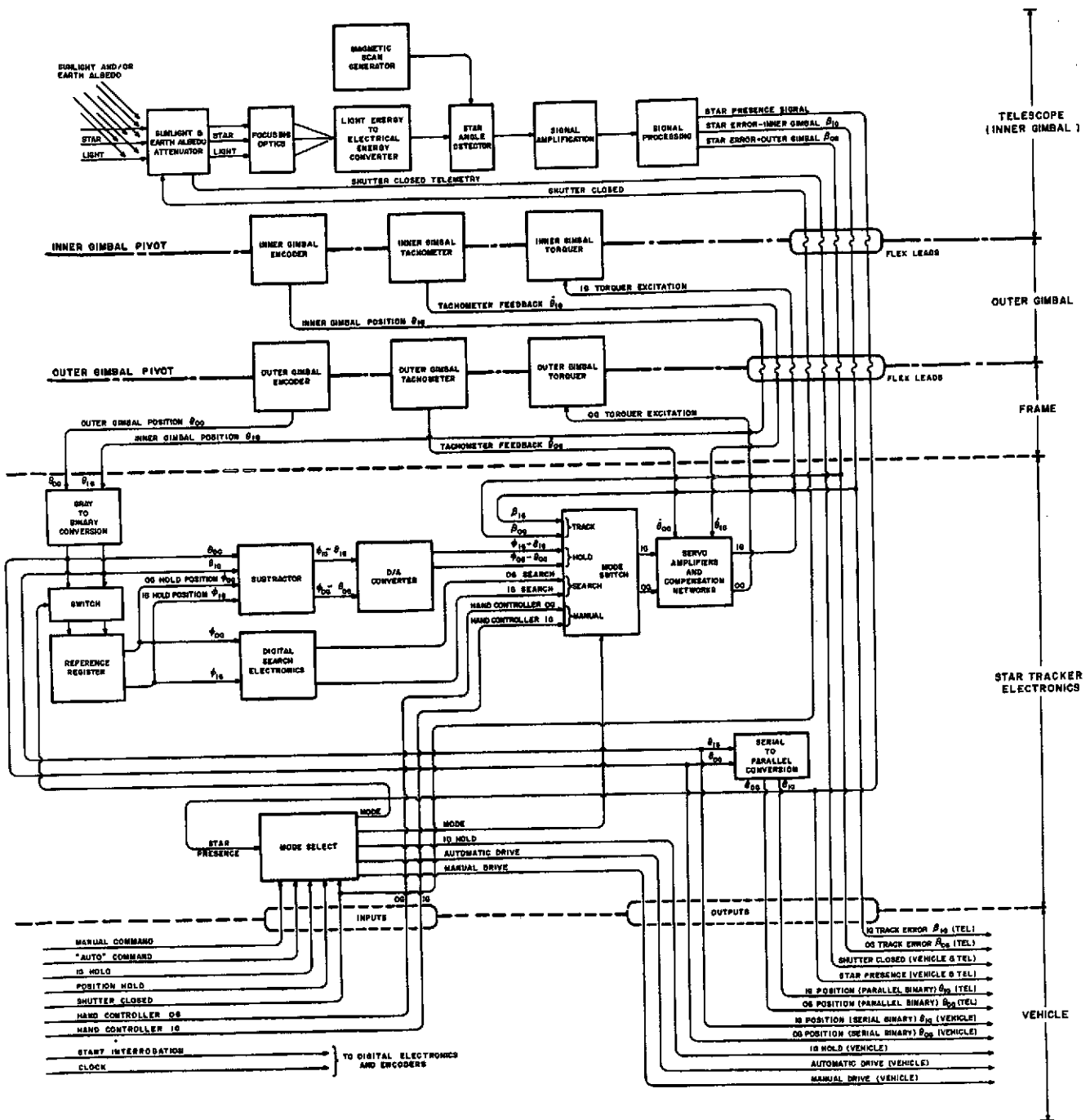
**SYSTEM FUNCTIONAL BLOCK DIAGRAM
FIGURE 2.1.2-1**

SYSTEM PICTORIAL BLOCK DIAGRAM

FIGURE 2.1.2-2

(1)   However, if in (k) the star tracker is aligned
       more than $\pm$ 30arc min from the star line-of-sight,
       the tracker enters the acquisition Search Sub-
       Mode.

2.1.1.3   Cluster Occultation of the Reference Star

When the reference star is about to be occulted by an
obstruction of the cluster in the tracker's normal
field-of-view, a Hold Mode discrete is issued from the
airborne digital computer. Information concerning the
obstructed regions is stored in an on-board memory or
originates from ground system control. A cluster
occult alarm is displayed whenever Ψ_{1c} and Ψ_{3c} indicate
an occulted tracker orientation. At this time, the
astronaut notifies the computer and ground control that
an alternate reference star is to be used for the solar
roll reference and to keep the $\overline{1}_{xv}$ spacecraft axis in
the orbital plane.

2.1.2   System Description

2.1.2.1   Block Diagrams

A functional block diagram of the Star Tracker is
shown in Figure 2.1.2-1. Functions contained within
the inner gimbal, the outer gimbal, and those in elec-
tronics are clearly separated. In addition, a pictorial
block diagram of the system is shown in Figure 2.1.2-2.

2.1.2.2   Star Tracker - ATM Interface

The Star Tracker interfaces with the ATM Digital Computer (ATMDC), the ATM Control and Display Panel (ATM C and D), the ATM Experiment Pointing Electronics Assembly (EPEA), and telemetry. The more significant inputs and outputs are listed below.

Inputs from ATMDC

1.   An "inner-gimbal-readout-request" envelope for inner-gimbal encoder interrogation.

2.   An "outer-gimbal-readout-request" envelope for outer gimbal encoder interrogation.

3.   A 10 KHz clock signal to control the serial transmission of the inner and outer gimbal data words.

4.   An "Auto" discrete which places the tracker in the automatic mode of operation. This command cannot override a Manual command or a Shutter-Close/Hold command from the C and D panel.

5.   A "Shutter-Closed/Hold" discrete which places the tracker in the shutter-closed/hold mode of operation. This command cannot override a Manual command from the C and D panel.

Outputs to ATMDC

1.   Inner-gimbal position information, in serial binary form. The serial word is 15 bits in length, is transmitted MSB first at a 10 KHz rate, and has a scaling of 30 arc seconds per increment.

2.   Outer-gimbal position information, in serial
      binary form. This serial word is 15 bits in
      length, is transmitted MSB first at a 10 KHz
      rate, and has a scaling of 30 arc seconds per
      increment.

3.   Automatic mode indication

4.   Manual mode indication

5.   Shutter closed indication

6.   Star presence indication

Inputs from C and D Panel

1.   A "Star Tracker Off" command, which disconnects
      the primary power source and closes the shutter.

2.   A "Star Tracker On" command, which connects the
      primary power source and places the tracker in
      the Shutter-Closed/Hold mode.

3.   A "Manual" command, which opens the shutter and
      places the tracker in the manual mode of operation.

4.   An "Auto" command, which places the tracker in the
      Automatic (Search/Track) mode of operation.

5.   A "Shutter-Close/Hold command which places the
      system in the Shutter-Close/Hold mode of opera-
      tion.

Outputs to C and D Panel

1. Star Presence discrete
2. Shutter Closed discrete
3. Automatic Mode discrete
4. Manual Mode discrete
5. Inner-gimbal direction
6. Outer-gimbal direction.

Inputs from EPEA

1. Inner-gimbal band controller drive signal in DC form.
2. Outer-gimbal band controller drive signal in DC form.

Inputs from Telemetry

1. Gimbal angle readout pulse.

Outputs to Telemetry

1. Inner gimbal angle in 15-Bit parallel binary format. The resolution is 30 arc seconds per increment.

2. Outer gimbal angle in 15-Bit parallel binary format. The resolution is 30 arc seconds per increment.

3. Star presence indication

4. Shutter closed indication

5. Inner-gimbal tachometer voltage

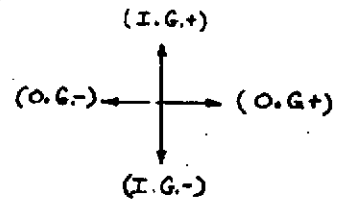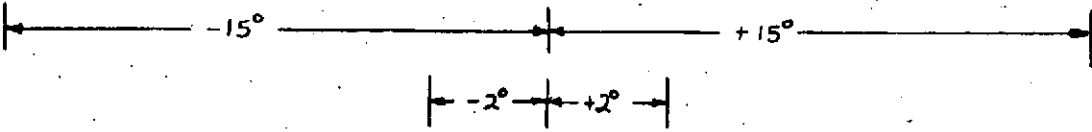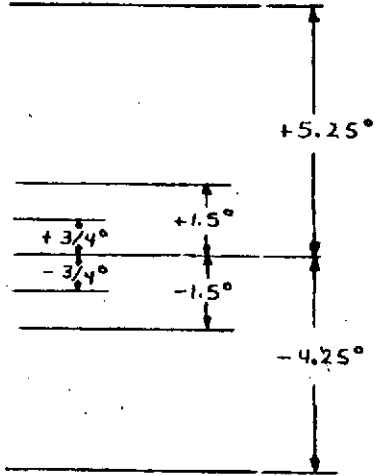6. Outer-gimbal tachometer voltage.
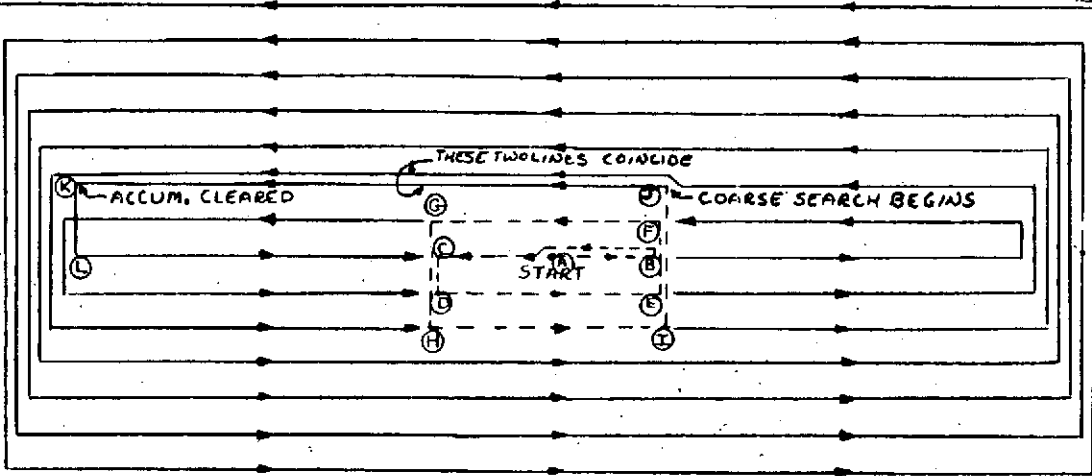
NOTE: DASHED LINES INDICATE FINE SEARCH
SOLID LINES INDICATE COARSE SEARCH

FIGURE 2.1.2-3

THE Bendix CORPORATION

ECLIPSE - PIONEER
DIVISION
TETERBORO, NEW JERSEY, U.S.A.

CODE IDENT NO.	SIZE	TWO AXIS GIMBAL
19315	B	SEARCH DIAGRAM
SCALE	WT		SHEET

2-14

2.1.2.3   Modes of Operation

The Star Tracker responds to three externally commanded
modes of operation: automatic, manual, and shutter-
close/hold. The operation of the tracker in each of
these modes is described below.

Automatic Mode

In the automatic mode, the tracker automatically search-
es for, acquires, and tracks the reference star. During
search, the gimbals are raster-scanned in two modes:
a fine mode in which a $\pm$ 2.5 degree by $\pm$ 2 degree area,
centered about the starting position, is searched,
followed by a coarse mode in which an angle of $\pm$ 15.5
degrees about the outer gimbal starting position and
+ 5.75 and - 4.75 degrees about the inner gimbal start-
ing position is searched. If a star has not been ac-
quired before the coarse search has ended, the inner
gimbal is returned to its initial position and the
coarse search pattern only is repeated until new com-
mands are received.

A diagram of the search pattern just described is given
in Figure 2.1.2-3. The general pattern is achieved
by rotating the outer gimbal at a fixed rate, while
holding the inner gimbal, and then holding the outer
gimbal while indexing the inner gimbal by a multiple
of $\pm$ 3/4 degree. Thus, the search pattern is character-
ized by a series of 4 degree or 30 degree sweeping
about the outer-gimbal axis with each sweep being
separated by 3/4 degree of inner-gimbal motion. Since
the acquisition field-of-view of the telescope is one

degree, the star will always be found during one of the outer gimbal sweeps; and hence, the outer-gimbal sweep speed should be as uniform as possible. To accomplish this, the outer gimbal is driven by a one deg/sec command applied directly to its rate loop, with the gimbal encoder being used only to determine when the proper angle ($\pm$ 2 degrees of $\pm$ 15 degrees from the initial angle) has been reached. The inner gimbal is indexed the required angle by means of its position loop, since uniformity of speed is unimportant along this axis.

When a star of proper magnitude enters the one degree acquisition field, an internally generated "End Search" pulse terminates the mechanical gimbal search, and, after a small time delay, switches the system to the Track mode of operation. In the Track mode, the inner and outer gimbals are controlled with error signals generated by the telescope electronics.

While tracking, should the star be lost (indicated by loss of the Star Presence signal), the system automatically reverts to the search operation. A fine search pattern, followed by a coarse search pattern, is generated, with the center coordinates being those at which the star was last tracked.

Manual Mode

The Manual mode is used to position the Star Tracker gimbals such that the target star is within the search limits of the automatic mode. A switch to the automatic mode then causes the star to be acquired and tracked.

If the star has been acquired in the Manual mode
(indicated by an active Star Presence signal), the
switch to the automatic mode results in immediate star
tracking.

The Manual mode is implemented by connecting the two-
axis DC inputs from the hand controller directly to the
appropriate gimbal rate loop. The telescope can then
be driven to any orientation within the gimbal limits.

Shutter-Close/Hold Mode

In the Shutter-Close/Hold mode, the shutter is closed
and both gimbals are held in a fixed position. This
position is the last position read out by the optical
encoders before the initiation of the mode.

The "hold" operation is accomplished by storing each
gimbal position readout in an "initial-position"
register. When the Shutter-Close/Hold command is re-
ceived these registers are no longer updated. Subse-
quent encoder readouts are then subtracted from the
words in the "initial-position registers, and the re-
sulting error signals are converted to analog voltages
which drive the gimbal position sensor to null.

2.1.2.4   Internal Operating Configurations

In response to the three externally commanded modes
(automatic, manual, and shutter-close/hold) the system
assumes several internal operating configurations. The
relationship between the system mode and the internal
servo loop configuration is tabulated below.

SYSTEM MODE	GIMBAL	SERVO LOOP	
		Error Source	Type
Manual	Both	Hand Controller	Rate
Shutter-Close/ Hold	Both	Digital Electronics	Position
Automatic (Search)	I.G.	Digital Electronics	Position
	O.G.	Digital Electronics	Rate *
Automatic (Track)	Both	Telescope Electronics	Position

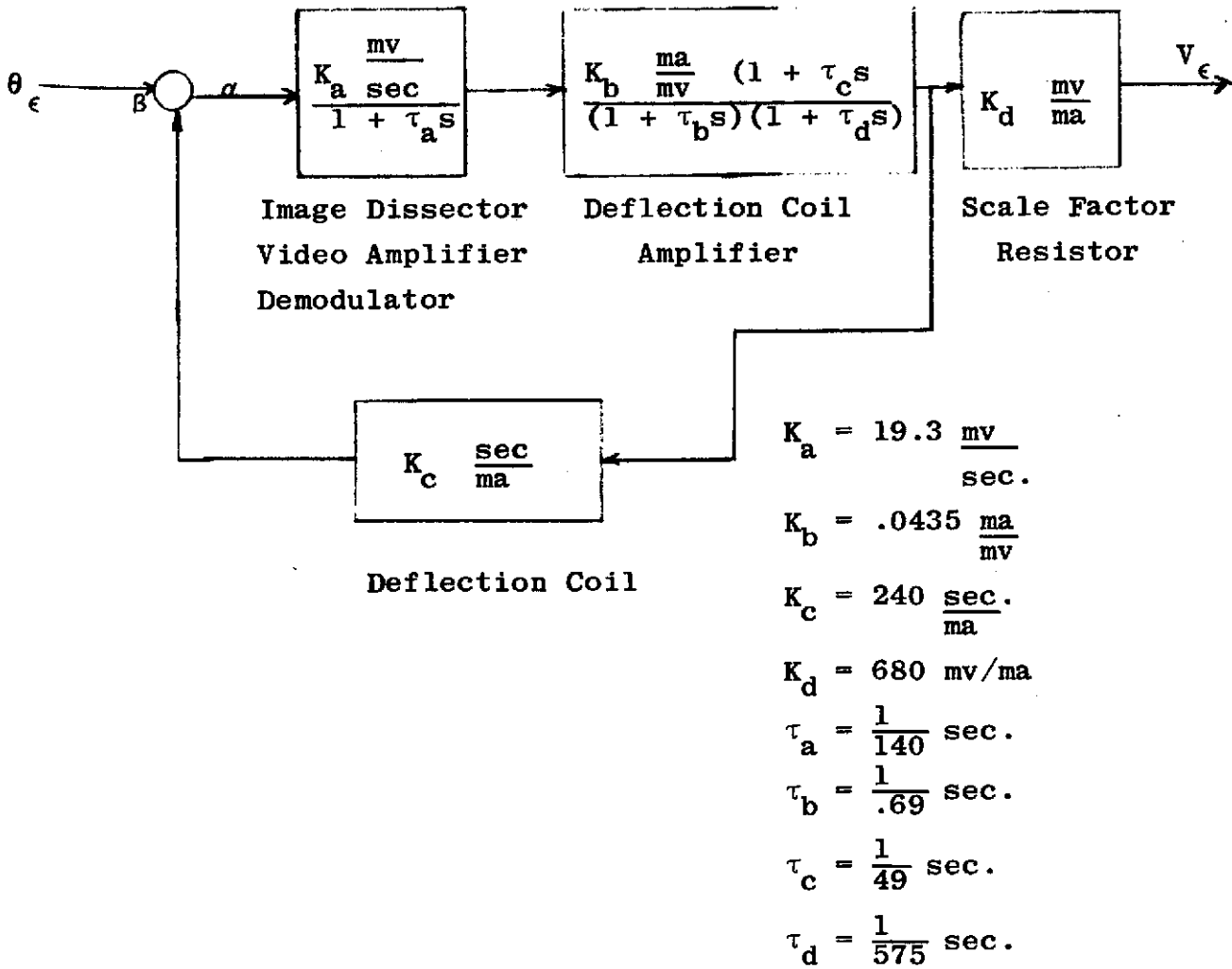* Encoder controls time duration of applied rate.

The various servo loops are described in the following sections.

2.1.2.4.1 Track Mode Servo Loop

The Track mode of operation is characterized by two servo loops, one all electronic in nature which centers the instantaneous field-of-view about the star line, and one electromechanical which aligns the telescope's optical axis, by torquing the gimbals, to the star line. Each of these loops is discussed below.

Electronic Tracking Loop

A block diagram of the Electronic Tracking loop is shown in Figure 2.1.2-4.

Image Dissector
Video Amplifier
Demodulator

Deflection Coil
Amplifier

Scale Factor
Resistor

Deflection Coil

$K_a = 19.3 \dfrac{mv}{sec.}$

$K_b = .0435 \dfrac{ma}{mv}$

$K_c = 240 \dfrac{sec.}{ma}$

$K_d = 680 \ mv/ma$

$\tau_a = \dfrac{1}{140} \ sec.$

$\tau_b = \dfrac{1}{.69} \ sec.$

$\tau_c = \dfrac{1}{49} \ sec.$

$\tau_d = \dfrac{1}{575} \ sec.$

ELECTRONIC TRACKING LOOP

FIGURE 2.1.2-4

The terms used in Figure 2.1.2-4 are defined as follows:

θ_ϵ = Angle between the star line and the telescope's optical axis.

B = Angle between the tracker's instantaneous field-of-view and the telescope's optical axis.

α = Angle between the star line and the instantaneous field-of-view of the tracker.

V_ϵ = Output voltage signal proportional to θ_ϵ.

The open-loop transfer function, A(s), of the servo loop is

$$1) \quad A(s) = \frac{K_a K_b K_c (1 + \tau_c S)}{(1+\tau_a S)(1+\tau_b S)(1+\tau_d S)} =$$

$$\frac{202 \left(1 + \frac{S}{49}\right)}{\left(1 + \frac{S}{.69}\right)\left(1 + \frac{S}{140}\right)\left(1 + \frac{S}{575}\right)}$$

and a Bode plot is shown in Figure 2.1.2-5.

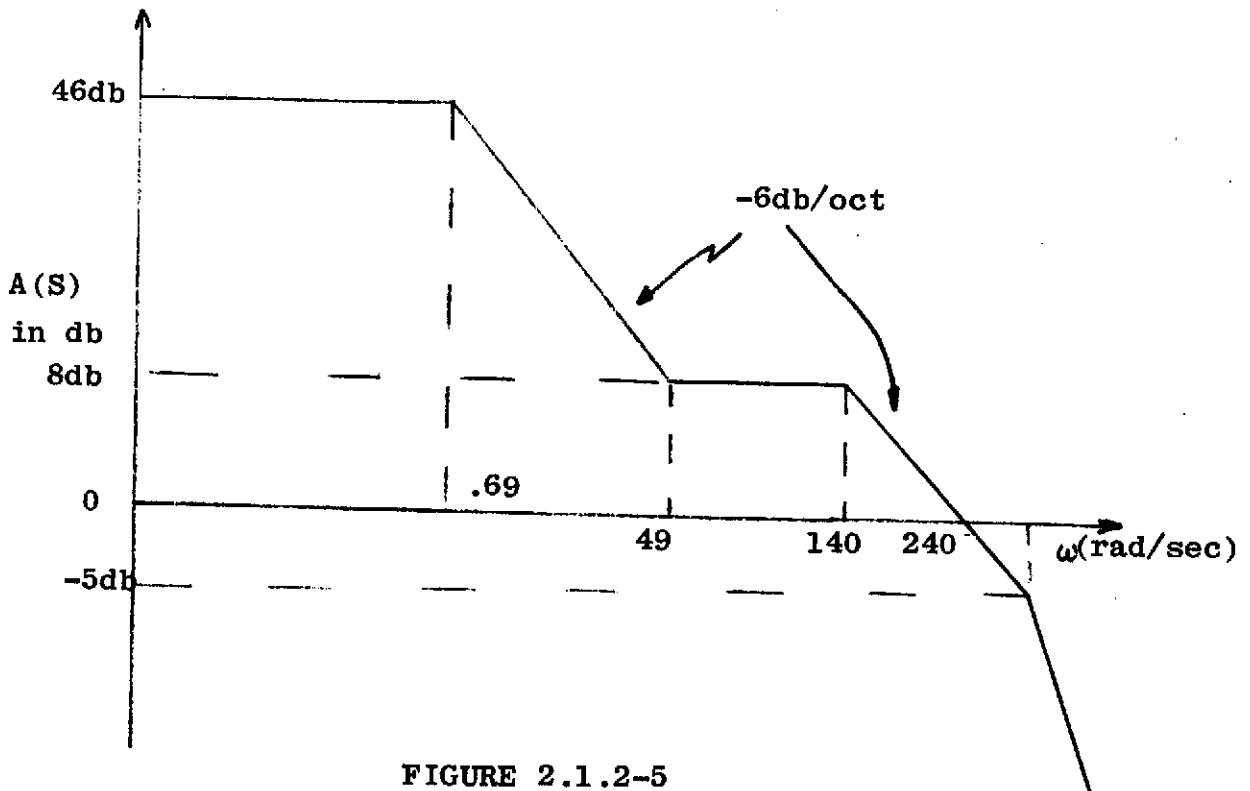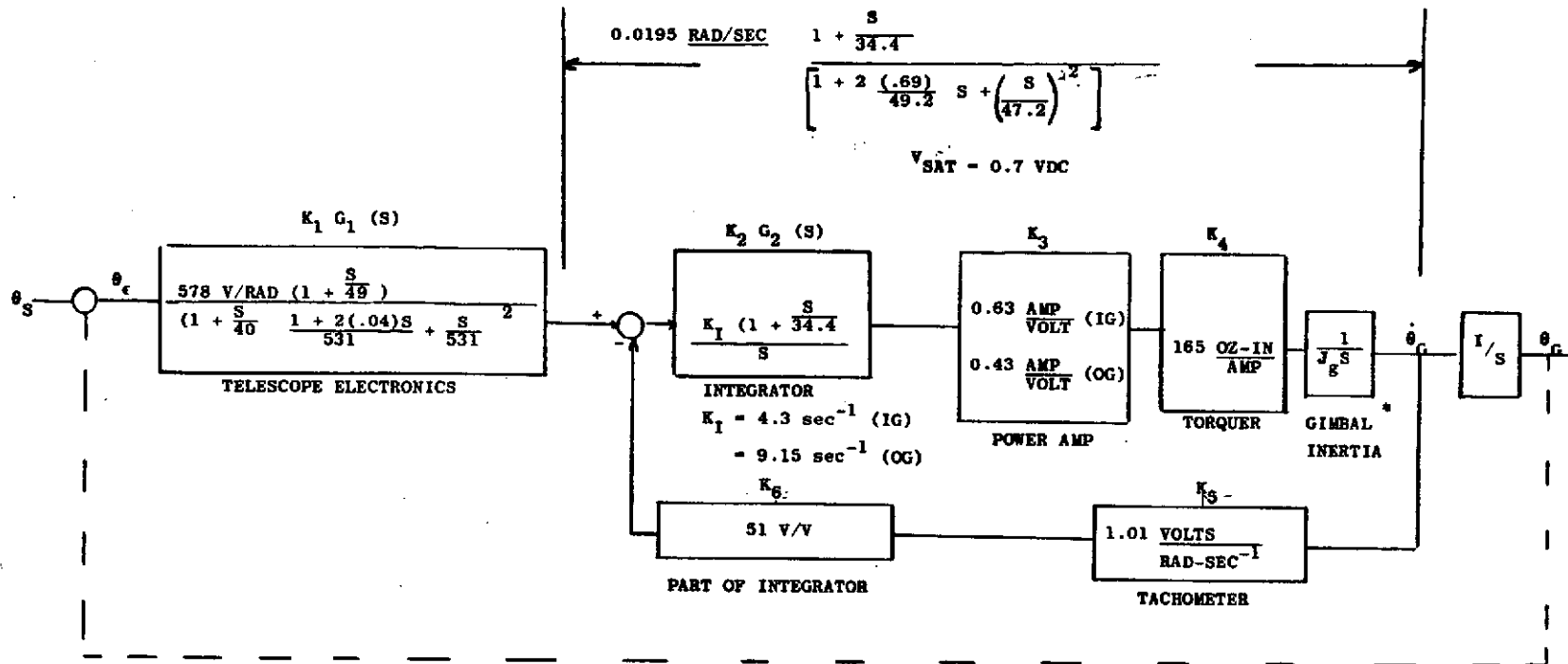FIGURE 2.1.2-5

The Bode plot shows the loop to be stable, (phase margin $\approx 85°$), and to have a cross-over frequency of about 240 rad/sec.

The closed-loop transfer function of the electronic tracking loop is:

$$\frac{V_\epsilon}{\theta_\epsilon} = \frac{2.8 \; \frac{mv}{sec} \; (1 + \frac{S}{49})}{(1 + \frac{S}{40}) \; \left[1 + \frac{2(.64)S}{531} + \frac{S}{531}^2 \right]}$$

$$0.0195 \text{ RAD/SEC} \qquad \frac{1 + \dfrac{S}{34.4}}{\left[1 + 2\dfrac{(.69)}{49.2}\ S + \left(\dfrac{S}{47.2}\right)^2\right]}$$

$$V_{SAT} - 0.7 \text{ VDC}$$

$K_1\ G_1\ (S)$

$$\frac{578\ \text{V/RAD}\ \left(1 + \dfrac{S}{49}\right)}{\left(1 + \dfrac{S}{40}\right)\left(\dfrac{1 + 2(.04)S}{531} + \dfrac{S}{531}\right)^2}$$

TELESCOPE ELECTRONICS

$+$ $-$

$K_2\ G_2\ (S)$

$$\frac{K_I\ \left(1 + \dfrac{S}{34.4}\right)}{S}$$

INTEGRATOR

$K_I = 4.3\ \text{sec}^{-1}$ (IG)

$\quad = 9.15\ \text{sec}^{-1}$ (OG)

K_3

$0.63\ \dfrac{\text{AMP}}{\text{VOLT}}$ (IG)

$0.43\ \dfrac{\text{AMP}}{\text{VOLT}}$ (OG)

POWER AMP

K_4

$165\ \dfrac{\text{OZ-IN}}{\text{AMP}}$

TORQUER

$\dfrac{1}{J_g S}$

GIMBAL INERTIA

$\dot{\theta}_G$

I/S

θ_G

θ_S θ_ϵ

K_6

51 V/V

PART OF INTEGRATOR

K_5

$1.01\ \dfrac{\text{VOLTS}}{\text{RAD-SEC}^{-1}}$

TACHOMETER

$*J_g = 16.5\ \text{oz-in-sec}^2$ (OUTER GIMBAL)

$J_g = 10.3\ \text{oz-in-sec}^2$ (INNER GIMBAL)

TRACK MODE SERVO LOOP
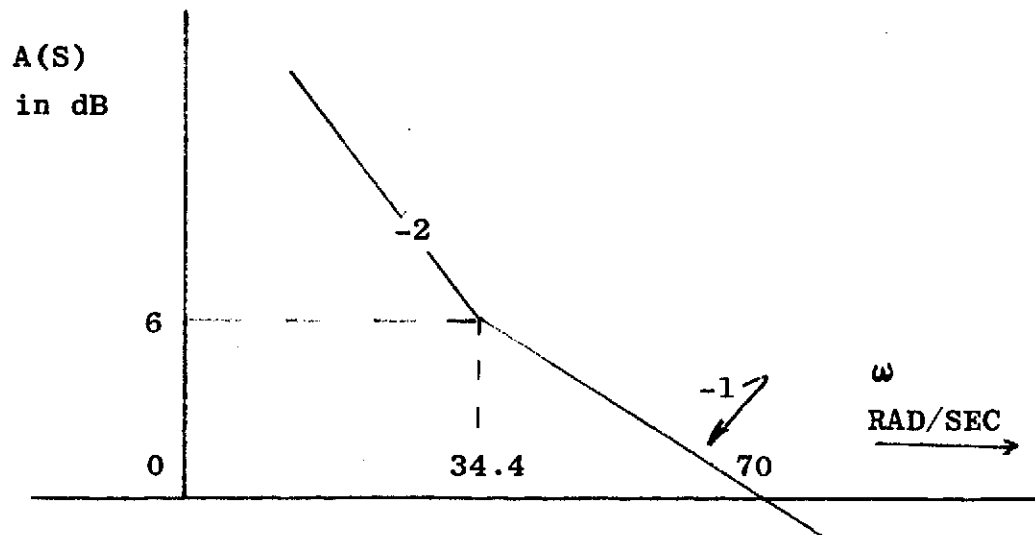
FIGURE 2.1.2-6

Electromechanical Tracking Loop

A block diagram of the complete track mode servo loop
is shown in Figure 2.1.2-6, and consists of a rate loop
(inner loop) and a position loop (outer loop). Note
that K, G, (S) is the closed loop transfer function of
the electronic tracking loop just described.

The open-loop transfer function of the rate loop,
applicable to both inner and outer gimbals, is

$$A(S) = \frac{K_s K_3 K_4 K_5 K_6 G_2 (S)}{J_g S} = \frac{2230 \left(1 + \frac{S}{34.4}\right)}{S^2}$$

A Bode plot of this transfer function is shown in
Figure 2.1.2-7. The phase margin of the loop is
about 64 degrees and the crossover frequency about
70 rad/sec.

A(S)
in dB

BODE PLOT – RATE LOOP

FIGURE 2.1.2-7

The open-loop gain of the position loop, also applicable to both inner and outer gimbals, is:

$$A(S) = \frac{11.3 \left(1 + \frac{S}{34.4}\right) \left(1 + \frac{S}{49}\right)}{S \left[1 + \frac{S}{40}\right] \left[1 + \frac{2(.69)S}{47.2} + \left(\frac{S}{47.2}\right)^2\right] \left[1 + \frac{2(.64)S}{531} + \frac{S}{531}^2\right]}$$

An asymptotic Bode plot of this transfer function is sketched in Figure 2.1.2-8. The loop has a phase margin of 86 deg. and a zero dB crossover frequency of 11.3 rad/sec (1.8 Hz).

FIGURE 2.1.2-8

$0.0195 \frac{RAD/SEC}{VOLT}$ $\frac{\left(1 + \frac{S}{34.4}\right)}{\left[1 + \frac{2(.69)S}{47.2} + \left(\frac{S}{47.2}\right)^2\right]}$

SUBTRACTION UNIT

θ_{com}

$-$

$.153 \frac{VOLT}{BIT}$ / $1 + \frac{S}{170}$

D/A CONVERTOR

$V_{SAT} = 0.7 \text{ VDC}$

$\frac{K_I\left(1 + \frac{S}{34.4}\right)}{S}$

INTEGRATOR

$K_I = 43 \text{ SEC}^{-1} \text{ (IG)}$

$= 0.15 \text{ SEC}^{-1} \text{ (OG)}$

$0.63 \frac{AMP}{VOLT}$ (IG)

$0.473 \frac{AMP}{VOLT}$ (OG)

POWER AMP

$165 \frac{OZ-IN}{AMP}$

TORQUER

$\frac{1}{J_g S}$

GIMBAL INERTIA

$\dot{\theta}_G$

I/S

θ_G

$J_{g_{IG}} = 16.5 \text{ OZ-IN-SEC}^2$

$J_{g_{OG}} = 10.3 \text{ OZ-IN-SEC}^2$

$51 \frac{VOLTS}{VOLT}$

PART OF INTEGRATOR

$1.0 \frac{VOLTS}{RAD/SEC}$

TACHOMETER

$6876 \frac{BITS}{RAD}$

ENCODER
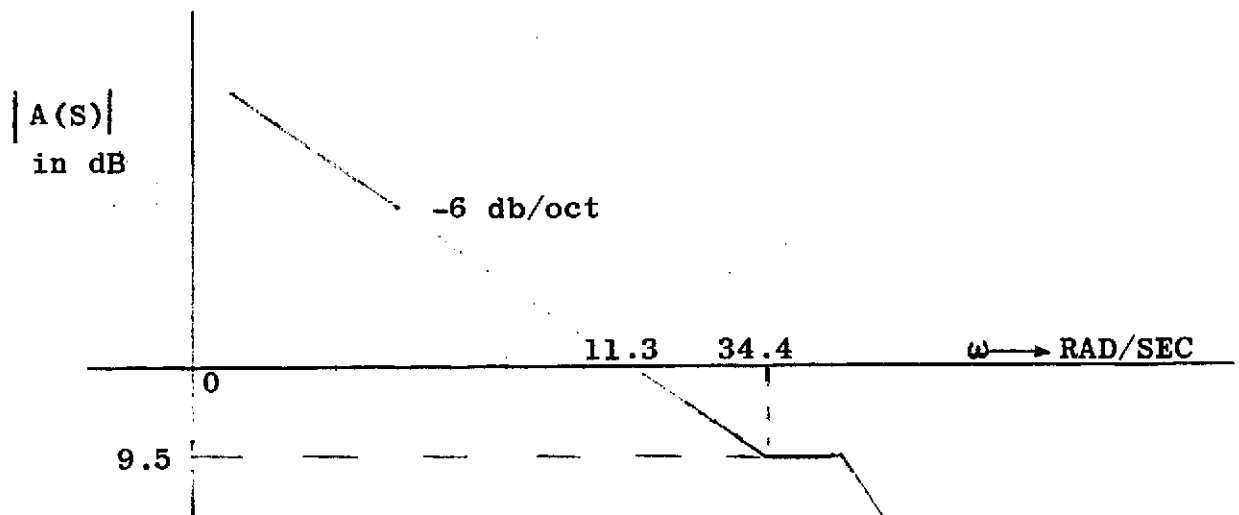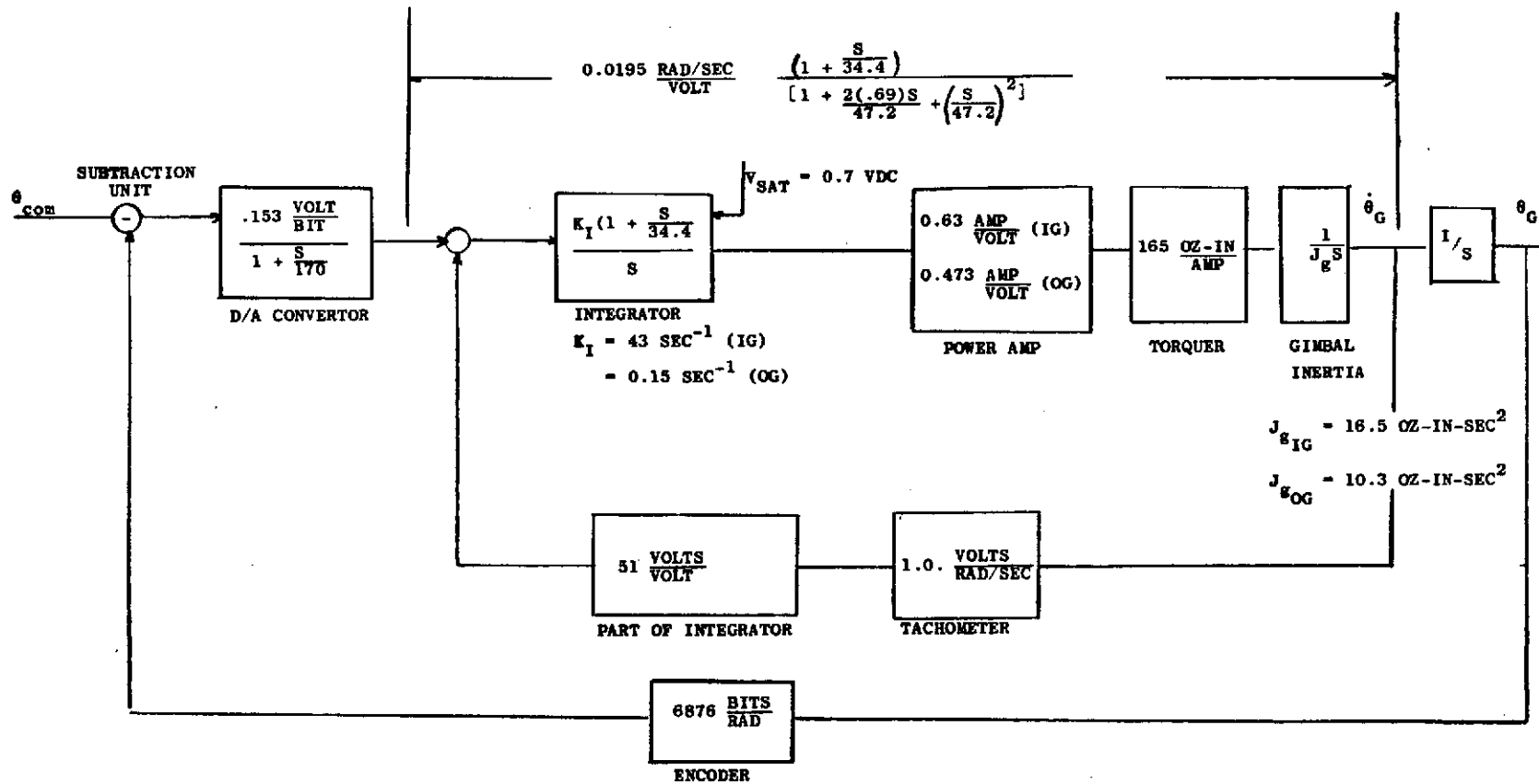
GIMBAL POSITION SERVO LOOP

FIGURE 2.1.2-9

2.1.2.4.2   Position Hold Loop

In the Shutter-Close/Hold mode, position-type loops are configured to hold both gimbals in a fixed position. This type servo loop is also implemented for the inner gimbal during automatic search, this time with the input command being a varying position.

The loop is similar in form to the track loop described in the previous section; the telescope and telescope electronics are replaced by a command register, digital subtraction unit, and D/A converter, and a digital encoder is used to provide the required feedback signal. A scaled block diagram of the inner and outer gimbal position loops is shown in Figure 2.1.2-9.

The open-loop transfer function of the position loop is:

$$A(S) = \frac{20.5}{S} \; \frac{\left(1 + \frac{S}{34.4}\right)}{\left[1 + \frac{2(.69)S}{47.2} + \left(\frac{S}{47.2}\right)^2\right]\left[1 + \frac{S}{170}\right]}$$

A Bode plot of this transfer function is sketched
in Figure 2.1.2-10. The loop has a zero dB cross-
over frequency of 20.5 rad/sec (3.27 Hz), and a
phase margin of 77.6 degrees.
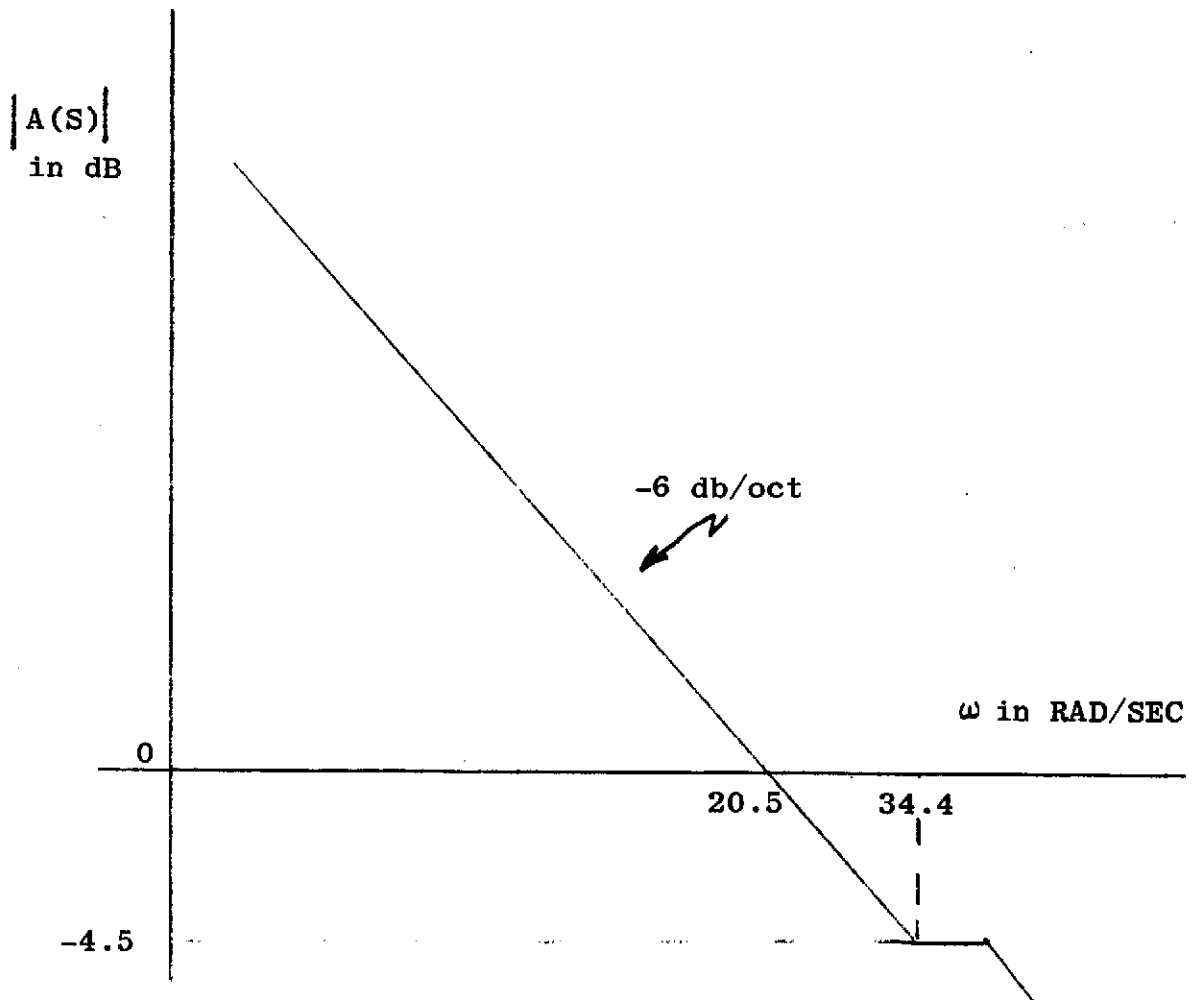
FIGURE 2.1.2-10

2.1.2.4.3   Manual Mode Servo Loop

In the Manual mode, DC signals from the hand con-
troller are routed directly to the gimbal rate loops,
the telescope electronics and D/A converters being
disconnected. In this mode the rate loop is char-
acterized by a scale factor of 0.224 deg/sec/volt.

2.1.2.4.4   Outer Gimbal/Automatic Search

The outer-gimbal loop configuration implemented
during automatic search is shown in Figure 2.1.2-11.
Reference to the figure shows that gimbal motion is
achieved by driving the outer-gimbal rate loop of
a constant speed, with the encoder being used to
determine the duration and polarity of the rate com-
mand.
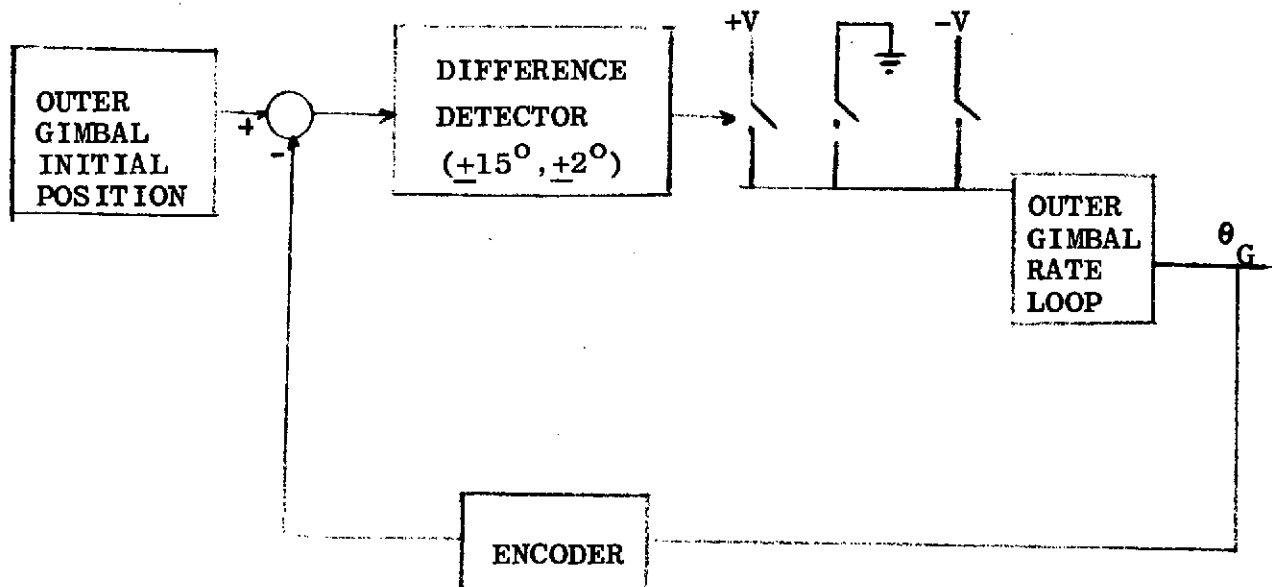
FIGURE 2.1.2-11

2.2   Telescope

The function of the telescope is to first determine
whether a star of proper magnitude is within the 1^O
field-of-view. When this occurs, a star presence signal
is generated. Secondly, it must supply coordinate
analog signals representing the error between the null
reference axis (optical axis) and the impinging star
line. When a proper star is located, a position feedback
loop is closed, through the servo amplifiers, between
these error-signals and the gimbal torquers, driving the
error to zero.

Star light initially enters the telescope through the sun
shade. The requirements of the sun shade are to reduce
the intensity of the oblique rays from the sun (13,600
lumens per cm^2) or earth (1600 lumens per cm^2 steradian
at 0.35 albedo) or other obstruction reaching the lens
and subsequently the detector. This level must be lower
than the intensity of Canopus and Achernar (the sun
attenuation must be approximately 10^{13}).

The collimated star light is then focused by an acromatic
lens through a reflecting wedge onto the photocathode
face of the detector. The 1.0 inch clear aperture of
the lens is sufficient to collect sufficient star light
energy to generate a high signal-to-noise ratio, a
figure of merit inversely proportional to the magnitude
of the telescope accuracy. The reflecting wedges not only
folds the light path, thus reducing the overall package
length, but also act as a mechanical nulling device
through rotation on their mounts to align the optical
axis of the telescope to the mounting pads during
assembly.

Light energy is converted to electrical energy at
the photocathode surface. The tube used is an S-20
type, ruggedized combination image dissector and multi-
plier tube (ITT FW 143) with high cathode sensitivity
(250 micro amperes per lumen) and high gain (2.5×10^6).
The operation of the detector is such that electrons
coming off the photocathode, from the point of focused
star light, are subsequently accelerated by a 600 volt
potential. (An additional 1400 volts is applied across
the dynode section). They are then electrostatically
focused by another field at the plane of the square
field aperture. The size of this instantaneous aperture
represents a field-of-view of 10 arc minutes. Electrons
entering the aperture are multiplied by a chain of 16
dynodes resulting in an anode signal current.

A magnetic coil encircles the image dissector portion of
the tube, the area between the photo-cathode and square
aperture. The coil deflects the electron beam such that
electrons emitted from a relatively large area of the
photocathode can be deflected so as to pass through the
aperture.

Essentially, star position information is obtained by
electronically measuring the distance between the
focused point of star light on the photocathode and the
null point. (Star line coincident with the optical
axis). This distance is proportional to the angle
between the star line and optical axis.

The detection system measures this distance by measuring
the magnetic coil current necessary to deflect the

electron beam through the center of the 10 arc minutes
square aperture. The x and y coordinates of this
current are the error signals used in the feedback
loop to position the telescope.

During the Acquisition mode, the electron beam is
scanned in a raster pattern over a 1° square. This can
be depicted as if the 10 arc minute square instantaneous
field-of-view if being scanned over the 1° square.

When a star of proper magnitude enters the field, the
raster scan currents are held and a small amplitude
cruciform scan is superimposed on the raster scan. The
amplitude of the cruciform is 10 arc minutes in the
positive and negative directions of each of the two
coordinate axes. Thus two axes information is generated.
This scan produces a modulated star position signal which,
after demodulation, represents the distance between the
star image and the center of the instantaneous 10 arc
minute field. These relatively small coordinate signals
are used to modify the raster scan currents and thus
bring the star image to the center of the instantaneous
field.

If the system is in track mode, the loop between these
telescope error signals and gimbal torquers will drive
the optical axis into alignment with the star line. The
telescope also provides for protective sensors to close
the protective shutter when the sun comes within 45°
and the earth comes within 5° of the optical axis. The
earth angle triggering point assumes an albedo of 0.35.

The ATM Tracker Sunshade can provide tracking to within 5° of the earth. When the earth, or other equal intensity object, moves within less than this angle, the telescope will not track to the specified accuracy. Actual protection of the detector is not required until a smaller angle is reached.

2.3   Optical System

For star trackers the important subsystem, which initiates the performance of the tracker is the optical system. While the sun shade attenuates all oblique light, the optics collect radiant energy from the star and image the star onto the photosensitive surface of the image dissector.

2.3.1   Objective Lens with Prism

The optics of the Bendix star tracker systems consist of an acromatic doublet and 2 aluminized reflecting wedges. The objective lens is a 6.833 inch focal length, F/4.6, aplanatic doublet. The major considerations taken into account in the lens design are good imagery in the spectral range from 365 Mμ to 800 Mμ, and the use of radiation protection (non-browning) glasses. The objective has a 1.500 inch clear aperture stopped to 1.00 inches by a baffle in order to attenuate stray light and to reduce the total sunshade length. The wedges used with the objective is employed to fold the optical path, therefore, yielding a more compact telescope assembly.

2.3.1.1   Image Quality

In the image plane of the optics, the star image blur circle is less than 0.002 inch diameter and contains approximately 80% of the star energy transmitted through the components.

2.3.1.2   Lens Design and Transmission Characteristics

The objective was designed to function with the wedges used to fold the optical path. The front element of the objective is made of Schott BK7G, a boroscilicate crown glass doped with cerium oxide to provide radiation protection. An air space exists between the front element of the objective and the rear element. The rear element of the objective is made of Schott LF5G, a light flint also doped with cerium oxide. The transmission characteristics of the two glasses are given in Figure 2.3.1.2-1.

From the figure it can be seen that the transmission characteristics of the two glasses remain with 90% of the initial values after being subjected to radiation dosages of 10^6 rads.

2.3.1.3   Stray Light Attenuation

An optical coating (Luxorb) is applied to areas of the lens element edges which do not transmit or reflect the star light energy. This reduces off-axis stray light. Unless substantially attenuated, the stray light can, through multiple internal reflections, reach the detector and appear as extraneous noise. According to the Fresnel Equation of Reflection, light is reflected when- ever it is incident on surfaces where there is a difference
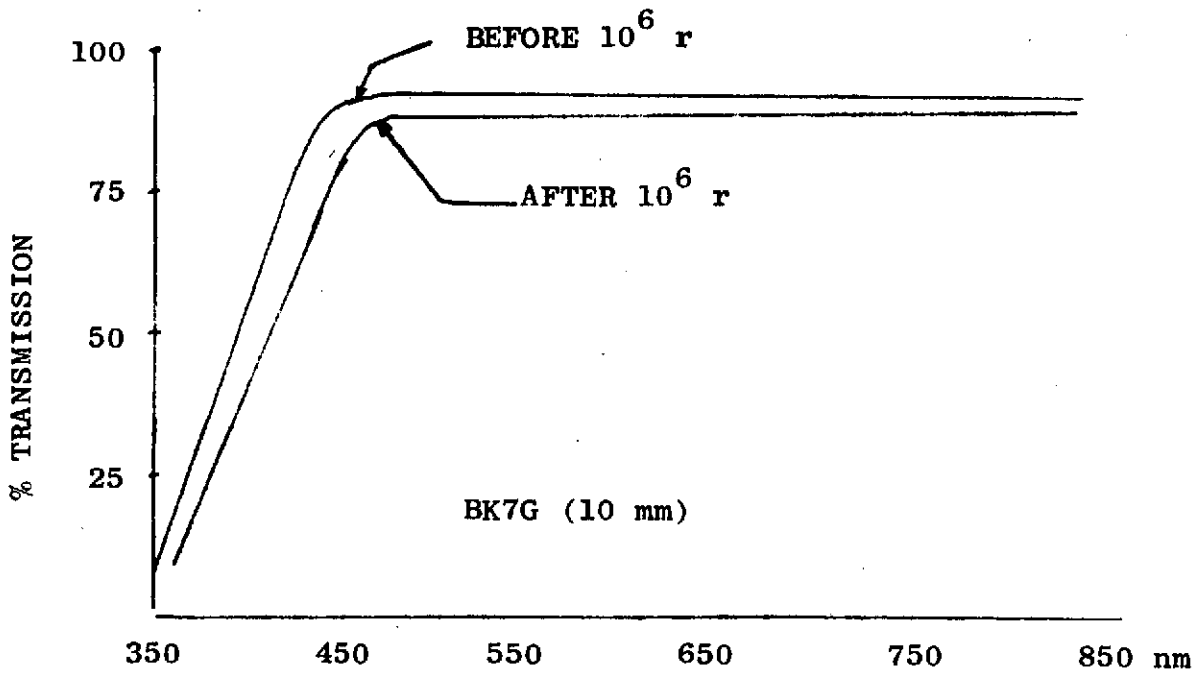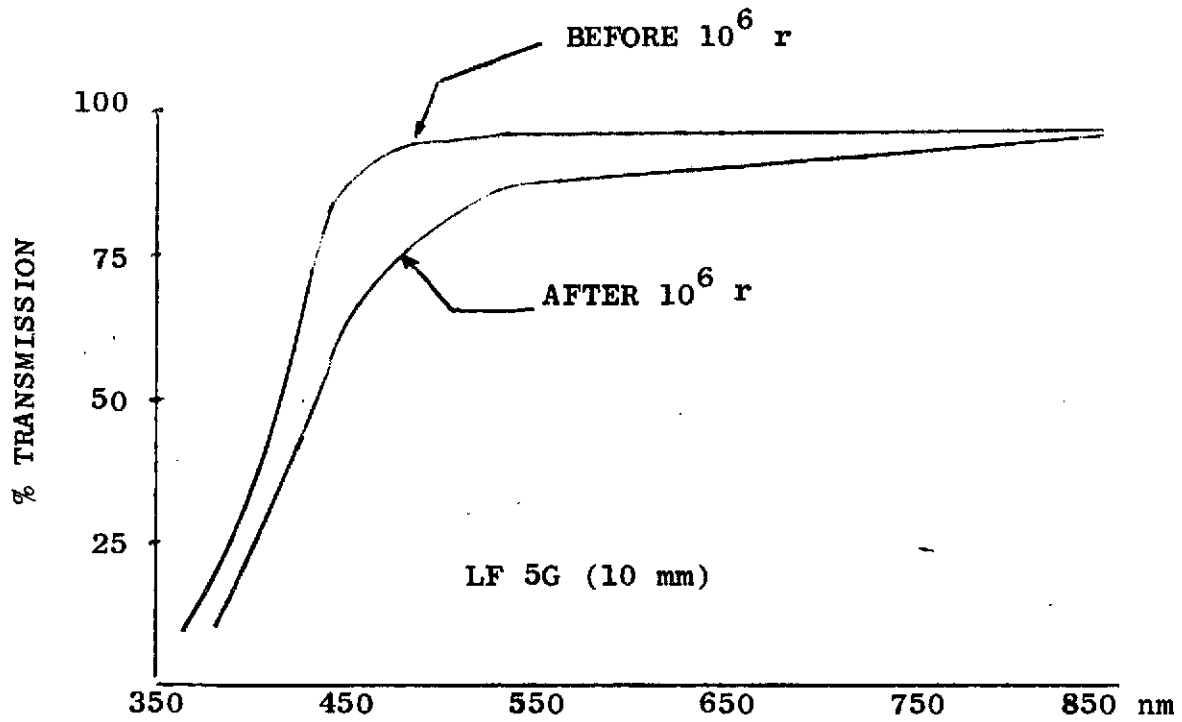
LENS ELEMENT RESISTANCE TO RADIATION

FIGURE 2.3.1.2-1

of optical index on both sides of the surface. The
index of refraction of the Luxorb used is matched to the
third decimal point to the glass on which it is applied.
Therefore, reflection virtually does not occur at the
glass-Luxorb interface, and the light is absorbed by dyes
which are an ingredient of the Luxorb. Reflection
attenuations on the order of 10^{-5} have been experimentally
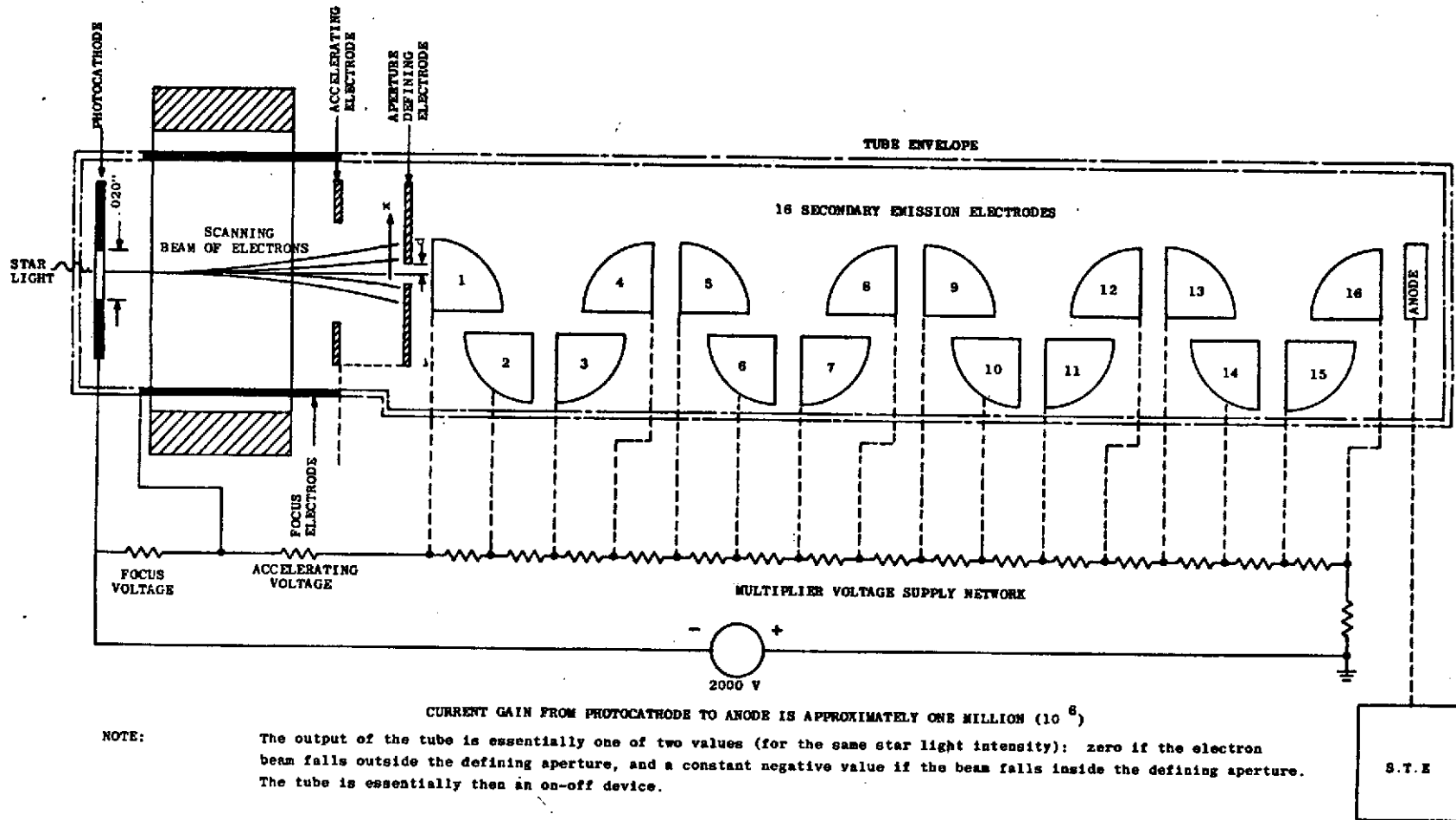verified by tests performed at Bendix.

2.3.1.4   Lens Housing

The lens housing of the star tracker objective is made of
beryllium. The housing is vented so that the air in the
air space can be bled off, thus eliminating unnecessary
stress upon the optical elements when the ambient becomes
the hard vacuum of space. From thermal analysis it has been
shown that the lens assembly will have a temperature ex-
cursion in space operation of slightly greater than $100^{\circ}F$.

2.3.2   Detector

The detector provides the main system transducer which
converts the optical information of the star's position
to a workable electronic signal.

This is accomplished by an external magnetic coil and
the three main sections of the tube; the photocathode,
the electron lens system (of which the aperture is an
integral part) and the dynode multiplier. (See Figure
2.3.2-1). In operation, illumination from the star being
tracked is imaged onto the photoemissive cathode driving
off electrons which are accelerated toward the aperture.
During this interval two things occur. First, the
electron lens system converges the electrons and focuses

STAR TRACKER DETECTOR

FIGURE 2.3.2-1

CURRENT GAIN FROM PHOTOCATHODE TO ANODE IS APPROXIMATELY ONE MILLION (10^6)

NOTE: The output of the tube is essentially one of two values (for the same star light intensity):   zero if the electron
beam falls outside the defining aperture, and a constant negative value if the beam falls inside the defining aperture.
The tube is essentially then an on-off device.

Bendix

Navigation &
Control Division

them onto an aperture located in the electrostatic
image plane of the tube. Second, the external magnetic
coil, mounted around this section, systematically
deflects the electron image across the aperture. The
electrons gaining entrance through the aperture are
increased by dynode multiplication thus forming an "on"
signal. The electrons which are swept onto the plate
containing the aperture do not enter the multiplier,
hence an "off" signal is produced during this interval.
The information on the position of the star being tracked
is contained in the wave train of the on-off pulses.
It should be noted that this type of modulation scheme
is devoid of moving parts, thus improving the reliability
of the system.

The particular detector used for the A.T.M. Star Tracker
is a ruggedized image dissector photomultiplier (ITT FW143).

The tube employs an S-20 (tri-alkali)photoemissive cathode.
The S-20 was chosen because of its high quantum efficiency
and low dark current. It is especially suited for tracking
Canopus since its spectral content peaks at approximately
the same wavelength as the spectral distribution of
Canopus, 4200 angstroms. The cathode response in the
blue end of the spectrum assists in providing a high
efficiency for tracking blue stars such as Achernar, while
maintaining sufficient sensitivity for acquisition and
track of Alpha Crux.

The electrostatic lens system employed in the proposed
detector consists of a focusing ring deposited internally
on the neck of the tube envelope and a square aperture.

The focusing feature increases resolution by reducing
the size of the electron image that is deflected across
the aperture.

In the plane of the electrostatic lens is an aperture,
0.014 inches on a side. Due to the geometry of the
tube, the accelerating potential, and the focusing
dynamics, the aperture is projected onto the photocathode
with a magnification factor of 1.4. This area, 0.020
inches, and the optical focal length, 6.833 inches,
produces an instantaneous field of view of 10 arc
minutes. The limited cathode area reduces the equivalent
noise input by minimizing collected thermionic emission,
at the same time maintaining high collection efficiency.
A reduction of dark noise by a factor of 36 is realized
in using the ten minute field of view as opposed to a 1
degree IFOV system with no loss to signal current.

Beyond the aperture is the multiplier section consisting
of 16 dynodes each of which exhibits secondary electron
emission characteristics of approximately 2.5. The
16 stages thus produces an overall electron gain of
approximately 2.5 million.

The anode, situtated beyond the multiplier, collects the
electrons and thus serves as the signal electrode.

Bendix has measured the dynamic characteristics of a
tube using a small (14 arc minute square) field of view
in conjunction with an external magnetic coil. The
purpose of the test was to locate the deflected star
electron image and thus determine the linearity charac-

teristics of the tube coil combination. The results
of scanning the electron beam over a field of view of
2^O x 2^O verified performance requirements.

2.3.3   Sun Shade

The sun shade has been tested successfully to within 40°
of the sun at the GE solar impingement-vacuum test
chamber at Valley Forge. Computer studies performed
by Bendix have confirmed an allowable earth light
impingement down to 5° (no adequate earth simulator
exists). Bendix has also determined mathematically
(by computer) that vehicle obstruction effects are
less than the effect of the earth.

2.3.4   Sensors

The Bendix Corporation has designed, developed and
fabricated for ATM use, two types of sensors, for the
purpose of providing the star tracker photomultiplier
tubes with protection from direct earth and sun illumi-
nation. Each type of sensors was individually designed
to operate at specific sun and earth angles over a wide
range of temperature variations to match their related
trigger electronics. These sensors have been tested and
qualified for ATM.

In order to provide a redundant protective system for
the star tracker, the sun and earth sensors each have
separate trigger electronics and have the capability
of reading to both, the sun and the earth.

For calibrating and testing these sensors, Bendix has
developed an earth albedo simulator and a 3000^OK two
degrees beam spread tungsten sun that has an energy

output equivalent to zero space sun.

Earth Sensor

The earth sensor is a photovoltaic device consisting of
three voltaic cells arranged in such a way to achieve
maximum sensitivity. This photovoltaic device provides
a signal which will trigger when the angle of the optical
axis to the earth's zenith is 5° maximum. The reflected
sunlight from the earth's albedo enters through an
objective lens and produces an image of the earth's
horizon. When the earth first comes into the field of
view, the first cell becomes operative and yields a
positive output. As the earth comes more and more in
the field of view, the second and third cells provide
an opposing negative signal to the first cell. The
output of all three cells is voltaic and is fed into a
high impedance circuit. Since the photovoltaic device
is required to operate over a significantly large tempera-
ture ranges, a thermistor is used to adjust the sensor
temperature coefficient to that of the related earth
trigger.

Specifications for the earth sensor and trigger electronics
are as follows:

Temperature: $\pm 1^O$ trigger angle $+25^O$C to -75^OC

Rotational Symmetry: $\pm 1^O$

Sensor Output Voltage: -200 mv $+25^O$C

Trigger Angle: 5° maximum with 35 Albedo

The earth sensor will not activate prematurely to the
sun at an angle greater than 45°.

Sun Sensor

The sun sensor is identical in construction and operation
to that of the earth sensor. Like the earth sensor it
serves as a protective device. It protects the photo-
multiplier tube from damage when the angle between the
sun rays and the optical axis is 45°. A feature of the
sun sensor is the use of an internal resistive network
that prevents the sun sensor from activating prematurely
against the earth at an angle greater than 5°.

Specifications for the sun sensor and related trigger
electronics are as follows:

Temperature $\pm 1^O$ trigger angle $+25^O$C to -75^OC
Rotational Symmetry: $\pm 1^O$ trigger angle
Sensor Output Voltage: -200 mv at $+25^O$C
Trigger Angle: 45° maximum

2.4   Electronics

2.4.1   Introduction

The electronics unit used with the Star Tracker is shown
in Figure 2.4.1-1 and may be divided into the following
functional sections: (1) Mode Selector, (2) Telescope
Electronics, (3) Servo Electronics, (4) Digital Logic
Unit, and (5) Power Supplies.

The Mode Selector acts as an interface between the Star
Tracker and the ATM input command discretes. This unit
transforms the voltage level of the input commands to one
compatible with the microcircuits used in the Star Tracker
electronics, and also logically combines the input commands
with a Star Presence signal to produce command signals to
which the tracker electronics can respond directly.
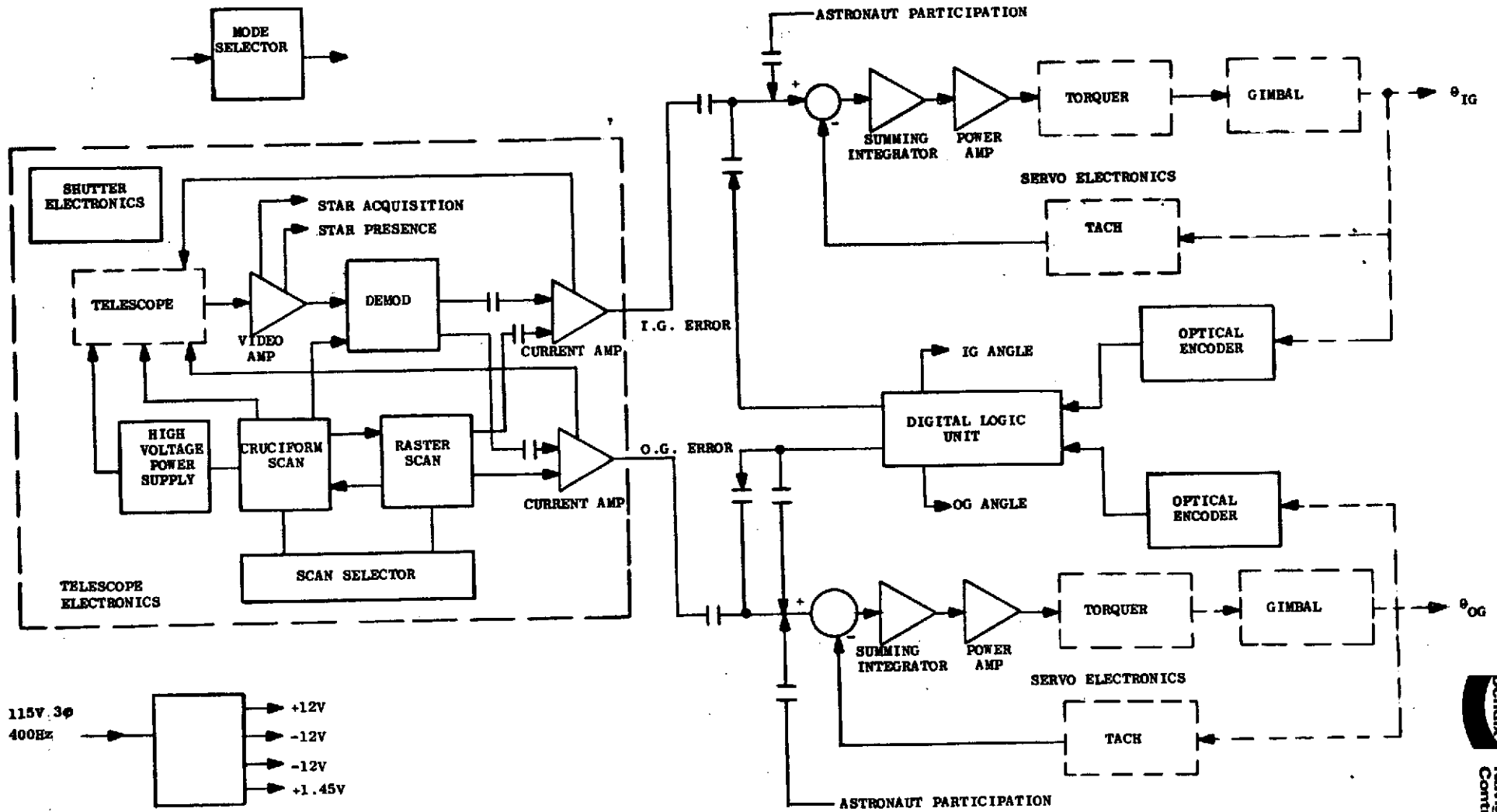
BLOCK DIAGRAM, ATM STAR TRACKER ELECTRONICS
FIGURE 2.4.1-1

The Telescope Electronics supply error signals to the
servo electronics proportional to the angle between the
star line and the optical axis of the telescope, and also
generate a Star Presence signal when the proper magnitude
star is within the field-of-view of the telescope. The
Telescope Electronics consist of the following sub-units:
(a) Video Amplifier, (b) High Voltage Power Supply,
(c) Raster Scan Electronics, (d) Cruciform Scan Electronics,
(e) Demodulator, (f) Scan Selector, and (g) Shutter
Electronics.

The Servo Electronics receive analog command signals from
Telescope Electronics, the Digital Logic Unit, and the
astronaut's Hand Controller, and supply the gimbal torque
motors with properly scaled and compensated drive signals.

The Digital Logic Unit (DLU) contains the electronics
required to perform a fine and coarse two-axis gimbal
search, and the electronics required to hold the gimbals
stationary. The DLU also provides the ATM digital com-
puter with the required inner and outer gimbal position
information.

The power supplies generate ±12 VDC, +5VDC and +1.45 VDC
regulated voltages.

Each of the functional units mentioned above is described
in more detail in the following sections.

2.4.2   Mode Selector Electronics
The Mode Selector constitutes the interface between the
ATM system and the Star Tracker, and logically operates

on the external input commands to produce command signals to which the Star Tracker can respond directly.

The Mode Selector receives the following inputs:

From Digital Computer

    1. Automatic Mode

    2. Shutter-Closed/Hold

From Control and Display Panel

    1. Manual Command

    2. Automatic Mode

    3. Shutter Closed/Hold

From Telescope Electronics

    1. End Search Pulse: A 200 m sec. pulse which indicates search is ending and the telescope electronics is switching to the track mode.

    2. Star Presence

    3. Shutter Closed

The Mode Selector provides the system with the following control signals.

1. Manual Command: This command activates relays in the servo loops and in the output interface.

2. Track Command: This command activates relays in the servo loops.

3. Search Command: This output notifies the DLU when the search mode is selected.

4. Output Gimbal Search Command: This command energizes a relay in the outer gimbal servo loop when the Search mode is selected.

5. Inner Gimbal Search/Hold Command: This command operates a relay in the inner gimbal servo loop when either the Search or Hold mode is selected.

6.   Hold Command: This command notifies the DLU when
     the Hold mode is selected.

7.   Outer Gimbal Hold Command: This command operates
     a relay in the outer-gimbal servo loop when the
     Hold mode is selected.

8.   Automatic Mode Indication: This output energizes
     a relay in the output interface when the Automatic
     mode is selected.

9.   Shutter-Close Command: This command is fed to the
     Shutter Electronics when the Shutter-Close/Hold mode
     is selected.

The operation of the Mode Selector is summarized in
Figure 2.4.2-1, and the circuit diagram is shown in
Figure 2.4.2-2.

2.4.3   Telescope Electronics

2.4.3.1   General Description

The telescope electronics supply the two-axis analog
error information required by the servo electronics,
and a Star Presence signal which indicates when the
desired star is within the field-of-view of the
telescope. The Star Tracker is characterized by two
fields-of-view, a one degree acquisition field and a 10
arc minute track field. The first of these, the acquisi-
tion field, is operative only during the time the star
search is being conducted. The second field, the tracking
field, is smaller than the first and is operative after
the star is operative after the star has been acquired.
The telescope electronics described in this section provide
this dual field capability.

A block diagram of the Telescope Electronics is shown in

PART NO.

LEGEND:

H: HOLD AND SHUTTER CLOSED
M: MANUAL
SC: SHUTTER CLOSED
S: SEARCH
T: TRACK

C+D — ON-OFF / SHUTTER CLOSED

C+D VIA CC — MANUAL / AUTO

DIGITAL COMPUTER — SHUTTER CLOSED / AUTO

STAR TRACKER — STAR PRESENCE / SHUTTER CLOSED

MODE SELECTION
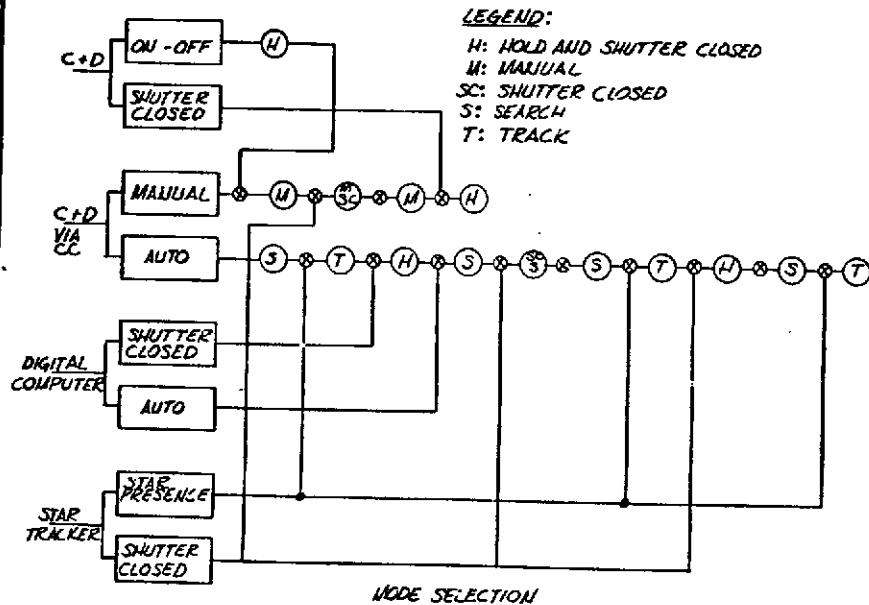
COMMAND	RESULTS
ON: C AND D	SHUTTER CLOSED AND HOLD.
MANUAL: C AND D VIA CC	MANUAL MODE; OVERRIDES ANY PREVIOUS COMMAND.
AUTO: C AND D VIA CC	SEARCH MODE: OVERRIDES MANUAL COMMAND.
STAR PRESENCE: STAR TRACKER	SYSTEM SWITCHES FROM SEARCH TO TRACK MODE; DOES NOT OVERRIDE MANUAL MODE.
SHUTTER CLOSED: D.C.	SHUTTER CLOSED AND HOLD; WILL NOT OVERRIDE MANUAL MODE.
AUTO D.C.	SAME AS AUTO FROM C+D EXCEPT WILL NOT OVERRIDE MANUAL MODE.
SHUTTER CLOSED: C AND D	SHUTTER CLOSED AND HOLD; OVERRIDES ANY PREVIOUS COMMAND.
SHUTTER CLOSED: STAR TRACKER	SHUTTER CLOSES AND SYSTEM REMAINS IN PREVIOUS MODE EXCEPT WHEN IN TRACK MODE IN WHICH CASE THE SYSTEM GOES INTO HOLD MODE.
DIGITAL COMPUTER DISCONNECT:	MODE SELECTOR DISREGARDS DIGITAL COMPUTER INPUTS.

✱ = INDICATES SUBASSEMBLY
✝ = VENDOR ITEM – SEE SOURCE CONTROL OR SPECIFICATION CONTROL DRAWING

HARDNESS

FINISH

– LIMITS OF ACCEPTABLE WORKMANSHIP ARE DEFINED IN NAVIGATION & CONTROL STANDARDS DS-103

UNLESS OTHERWISE SPECIFIED
– DIMENSIONS ARE IN INCHES
– TOLERANCES ON DECIMALS
2 PLACE   3 PLACE   4 PLACE
± .03   ± .005   ± .0005

MATERIAL

DR
CHK
ENGR
T.O.
MET
REL
APPD

CONTRACT NO.

☐ DO NOT MARK PART NO.
☐ MARK PART NO. AS SPECIFIED

PART REF
ORIGINALLY DESIGNED FOR 2126108

APPROVAL

APPROVAL
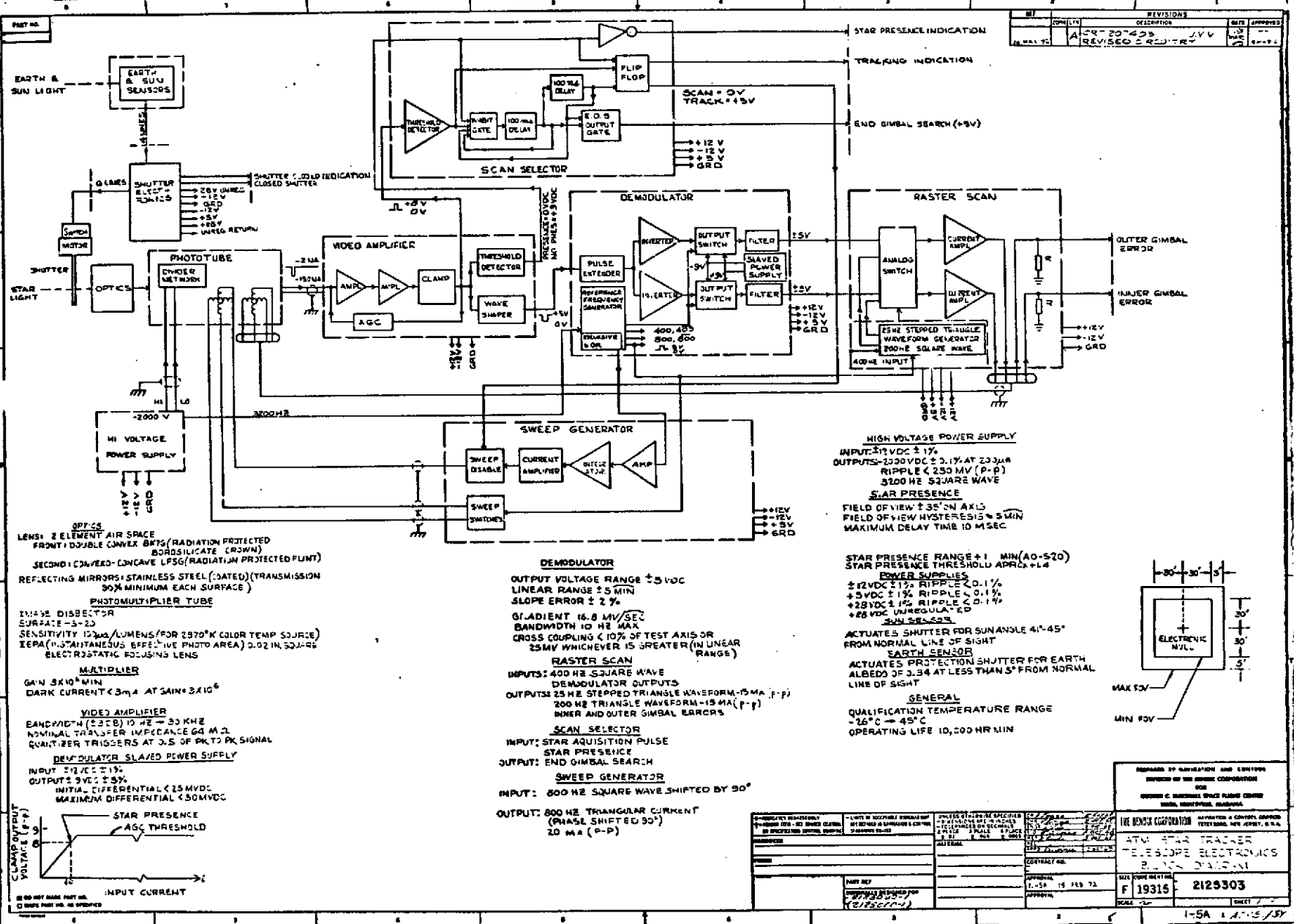
SCALE

SHEET 1 OF 1

FIGURE 2.4.2-1

FIGURE 2.4.2-2

Figure 2.4.3-1.   Included on the diagram are the per-
formance characteristics of the several functional
units comprising the electronics.

In the Search mode of operation the Raster Scan
Electronics produce the waveforms required to elec-
tronically scan the one degree acquisition field.
The scan pattern produced by these waveforms consists
of a linear sweep of the 10 arc minute instantaneous
field-of-view along one axis followed by a stepped
motion along the other.   When a star of proper magni-
tude enters the one degree field a "Star Acquisition"
pulse is generated by the Video Amplifier.

This pulse is accepted by the Scan Selector which, in
turn, generates an "End Search" pulse which terminates
the mechanical gimbal search, and, after a small time
delay, switches the system from the raster to the
cruciform scan.   A star presence signal is then generated
and the system switches to the track mode of operation.

In the Track mode the output signal from the Video Amplifier
is a modulated function of star position relative to the
instantaneous field-of-view of the telescope and is sent
to the Demodulator for further processing.   The Demodulator
gates this video signal with reference signals derived
from the 3200 Hz clock to produce a DC error signal
proportional to the misalignment angle between the star
line and the center of the instantaneous field-of-view
of the telescope.

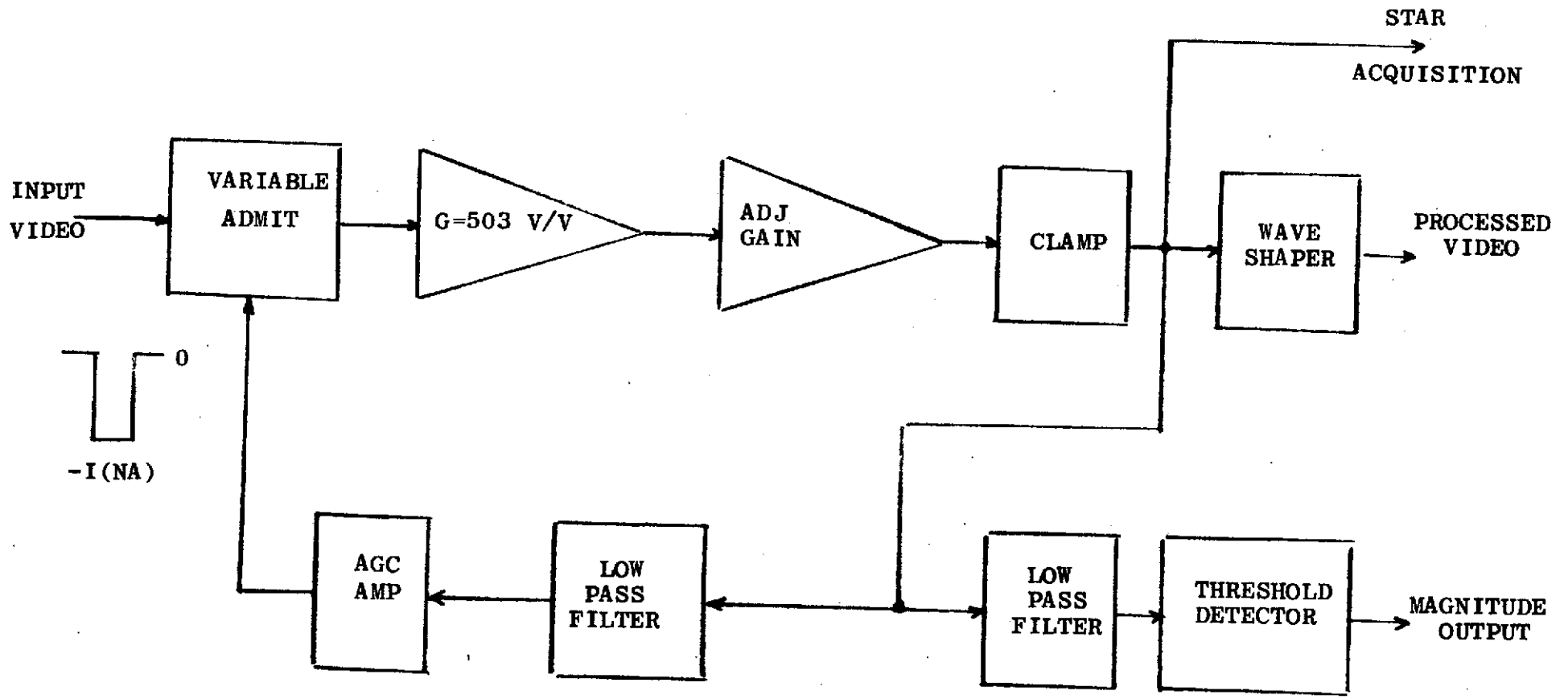The output signals from the Demodulator are sent to the

FIGURE 2.4.3-1

current amplifiers of the Raster Scan Electronics.
These amplifiers drive the deflection coils so as to
reduce the demodulator output signals to zero, which
results in the star line being brought into coincidence
with the axis of the instantaneous field-of-view of
the telescope. The resultant deflection coil currents
are thus proportional to the star line/optical axis
misalignment angle and therefore represent the analog
error signals required by the servo electronics. Thus,
in the Track mode, the telescope electronics form an
all-electronic tracking loop, independent of the gimbal
servo loops, in which the instantaneous field-of-view
of the telescope is brought into coincidence with the
star line.

A more detailed description of the units making up the
telescope electronics is given in the following sections.

2.4.3.2   Video Amplifier

The Video Amplifier receives current pulses from the
photomultiplier tube and processes these signals to form
the Star Acquisition signal, the Star Presence Signal,
and the modulated star-position error signals. The
first two processed signals are used by the Scan
Selector to determine the scan mode of operation,
and the error signals are used by the demodulator to
generate the DC signals required by the output current
amplifiers in the Track Mode. In addition, the Star
Presence signal is used to control the overall tracker
mode of operation. A block diagram of the Video
Amplifier is shown in Figure 2.4.3-2, and a circuit
schematic in Figure 2.4.3-3.

INPUT
VIDEO

VARIABLE
ADMIT

G=503 V/V

ADJ
GAIN

CLAMP

WAVE
SHAPER

PROCESSED
VIDEO

STAR

ACQUISITION

0

−I(NA)

AGC
AMP

LOW
PASS
FILTER

LOW
PASS
FILTER

THRESHOLD
DETECTOR

MAGNITUDE
OUTPUT

VIDEO AMPLIFIER BLOCK DIAGRAM

FIGURE 2.4.3−2

FIGURE 2.4.3-3

Basically, the Video Amplifier consists of a variable
admittance input branch coupled to a high-input-impedance
non-inverting fixed-gain stage of 503 V/V. The second
stage is an adjustable gain stage used to tailor the
phototube to the system. The gain of this stage is
adjusted so that the magnitude threshold detector
triggers for the threshold star.

The output of the second stage is clamped to -0.5V for
comparison to the magnitude threshold detector, scan
selector, threshold detector, processed video output
waveshaper and the AGC amplifier.

The processed video turns on at approximately one half
of the peak-to-peak value of the threshold star.

The AGC amplifier is set to turn on at a leverl 23%
above the level at which the magnitude detector turns
on. The AGC amplifier controls the variable admittance
input stage of the amplifier. The variable admittance
stage consists of a current divider network in which one
branch of the divider is a 10 meg resistor in parallel
with a field-effect transistor, whose drain-to-source
admittance is controlled by the AGC amplifier.

The low pass filters at the input to the magnitude
detector and AGC amplifier are for filtering any high
frequency spikes contained in the signal.

2.4.3.3   Raster Scan Electronics
The Raster Scan Electronics provide the waveforms
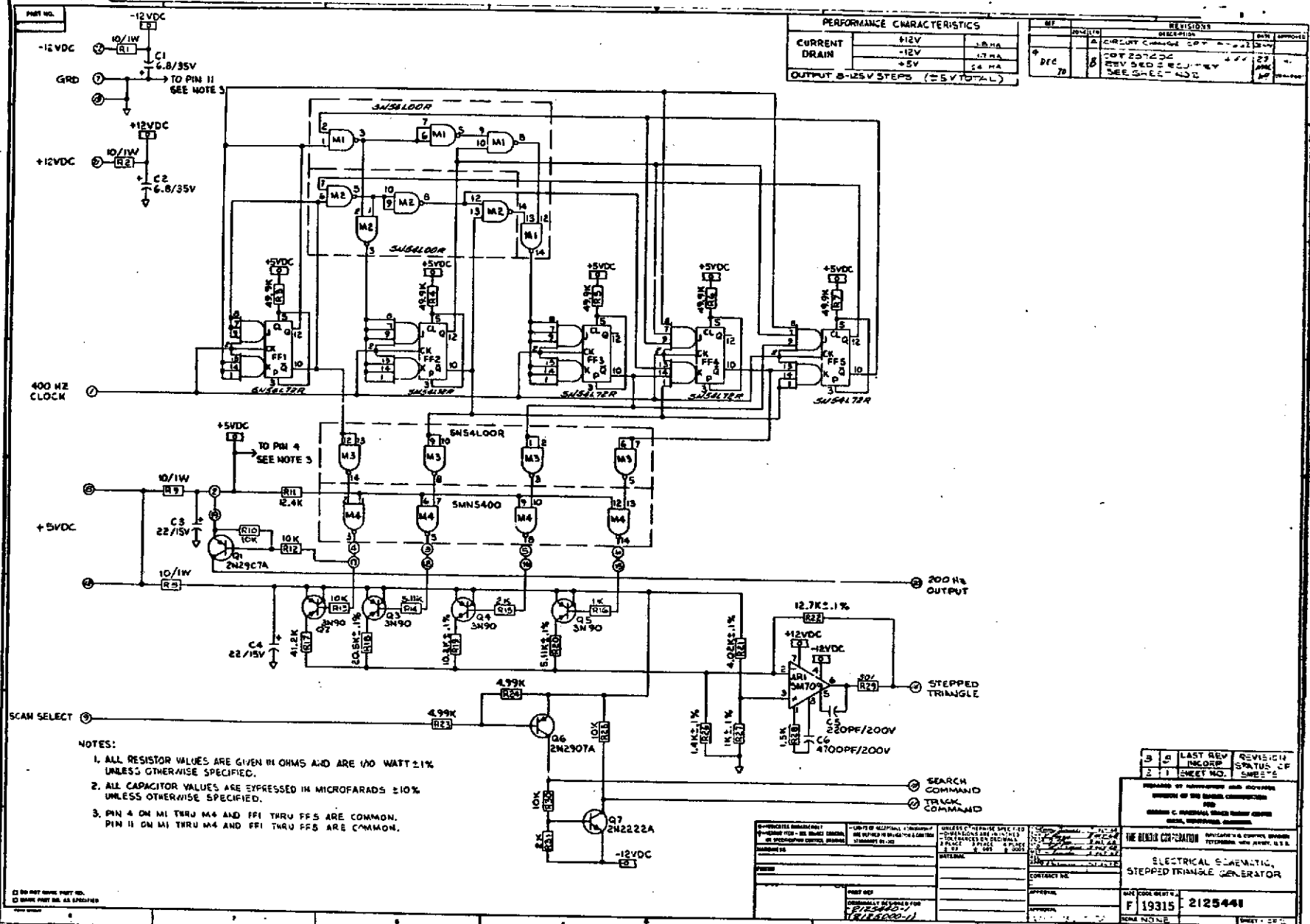required to electrically scan the one degree acquisition
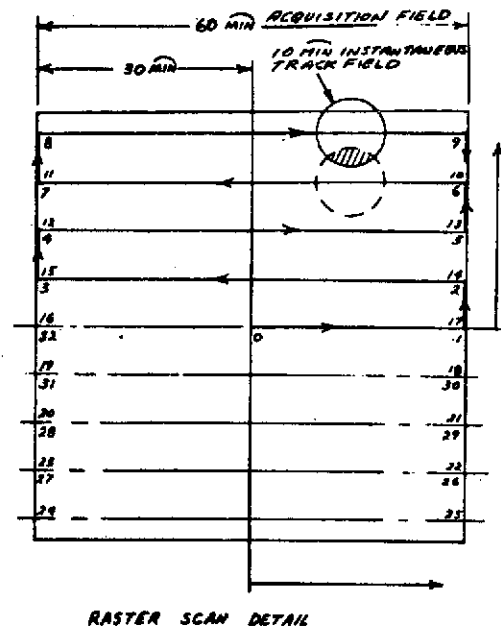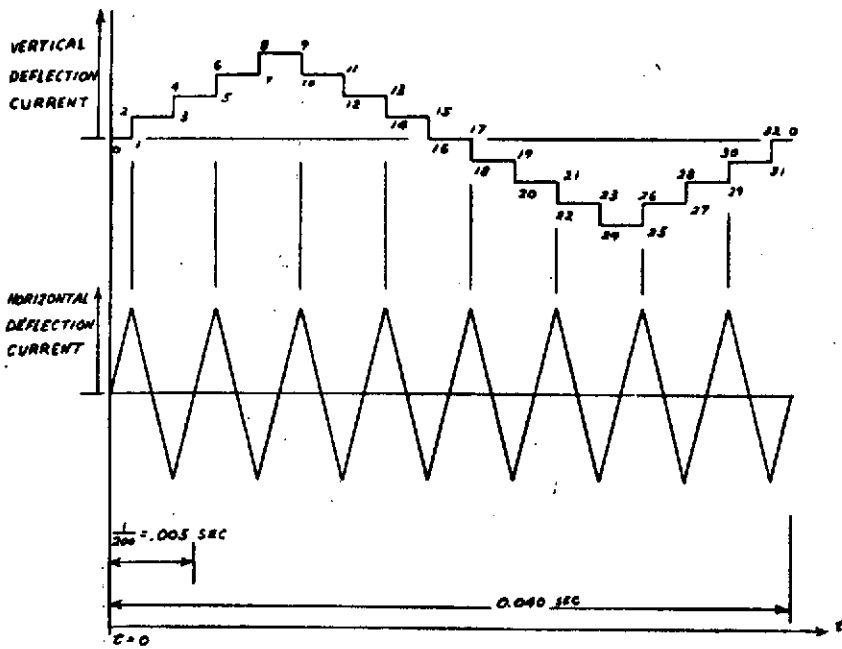
RASTER SCAN SEARCH PATTERN

FIGURE 2.4.3-4

field in the Search mode of operation, and provide the
output current amplifiers required to close the electronic
tracking loop in the Track mode of operation. The elec-
tronic scan of the one degree acquisition field is
accomplished by applying a linear 200 Hz triangular
current waveform to the horizontal deflection coils and
a synchronized 25 Hz stepped triangular current waveform
to the vertical deflection coils. The resulting search
pattern is illustrated in Figure 2.4.3-4 and shows the
one-degree field to be completely scanned every 20
milliseconds.

The Raster Scan Electronics consists primarily of a
stepped triangular waveform generator, an analog switch
assembly, and a pair of output current amplifiers, and
is shown in Figures 2.4.3-5 and 2.4.3-6. The stepped
triangular waveform generator (Figure 2.4.3-5) utilizes
a five-stage gated parallel counter which produces the
binary sequence 4 5 6 7 8 9 10 11 12 11 10 9
8 7 6 5 4 3 .... The output of the counter
controls the states of four digital switches which in
turn supply weighted currents to the operational ampli-
fier. The output of the amplifier is the desired stepped
25 Hz triangular waveform.

The linear 200 Hz triangular waveform is obtained by using
amplifier AR2 (Figure 2.4.3-6) to integrate the 200 Hz
square wave produced by the triangular waveform generator.
The analog switch assembly allows the search-mode wave-
forms to be connected to the output current amplifiers
in the Search Mode of operation, and the appropriate
Demodulator signals in the Track mode of operation.
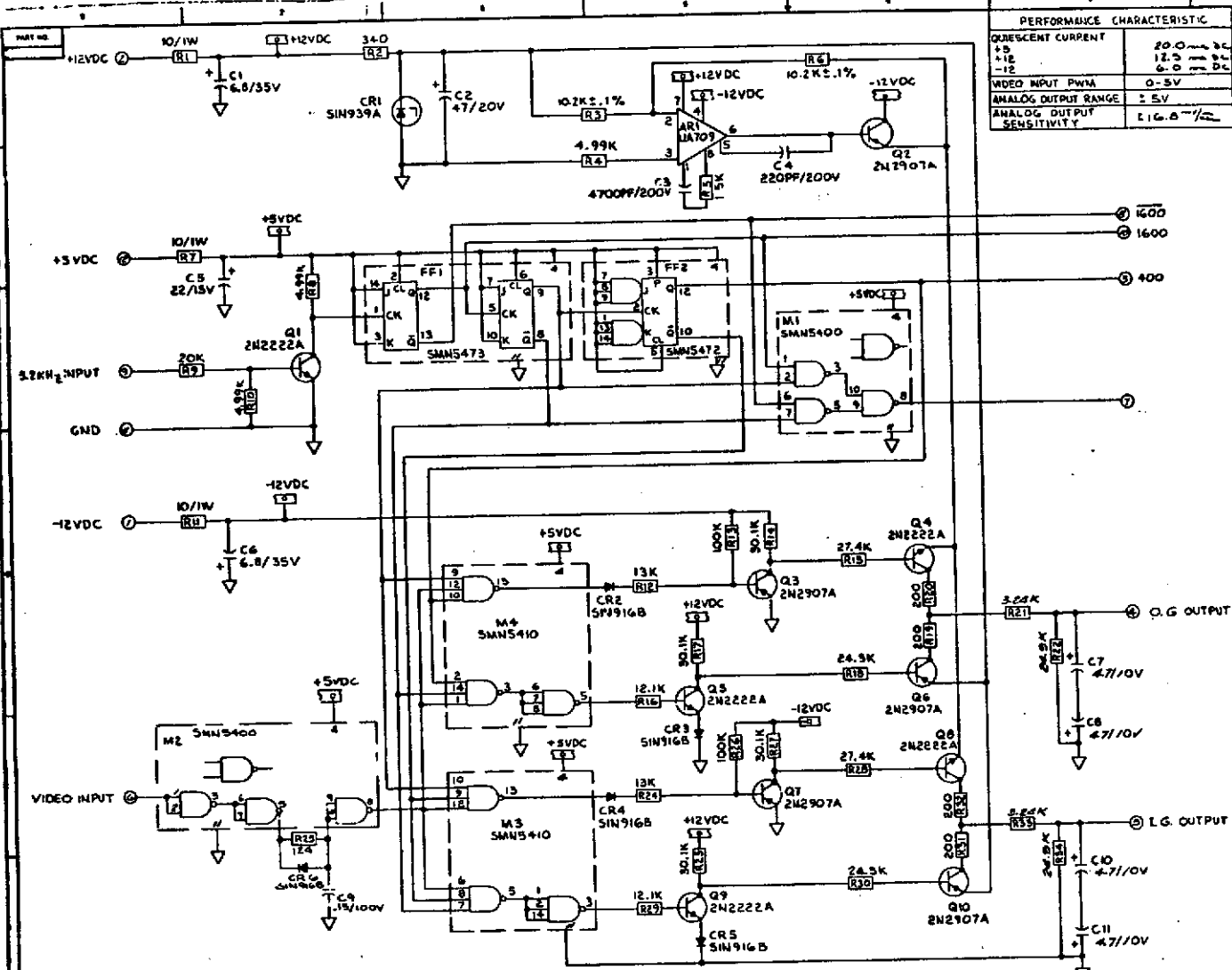
FIGURE 2.4.3-5

FIGURE 2.4.3-6

The output current amplifiers are used to provide the
deflection coil with a high-impedance drive source.
Each amplifier consists of an SM709G operational amplifier
with appropriate RC networks. In the Track mode, the
outputs of these amplifiers comprise the required
tracker error signals.

2.4.3.4   Sweep Generator

The Sweep Generator produces the cruciform scan pattern
required in the Track mode of operation, and is shown
in the schematic in Figure 2.4.3-7. In operation, the
800 Hz $/$ 90° waveform is accepted by a buffer circuit
which drives two temperature-compensated zener diodes.
The resultant square wave is fed to an integrator to
produce a triangular voltage waveform which is converted
to a triangular current signal by the current amplifier.
This current is alternately fed to the two deflection
coils by means of analog switches which are driven by
the 400 Hz input.

2.4.3.5   Demodulator

The Demodulator receives processed video signals from
the Video Amplifier and converts them into two-axis
analog error signals for use by the output current
amplifiers. A schematic of the Demodulator is shown in
Figure 2.4.3-8. The demodulator contains four basic
sections: a pulse extender, the inner-gimbal error circuitry,
the outer-gimbal error circuitry, and a regulated voltage
source. The inner and output gimbal error circuitry are
identical, except for their reference inputs.
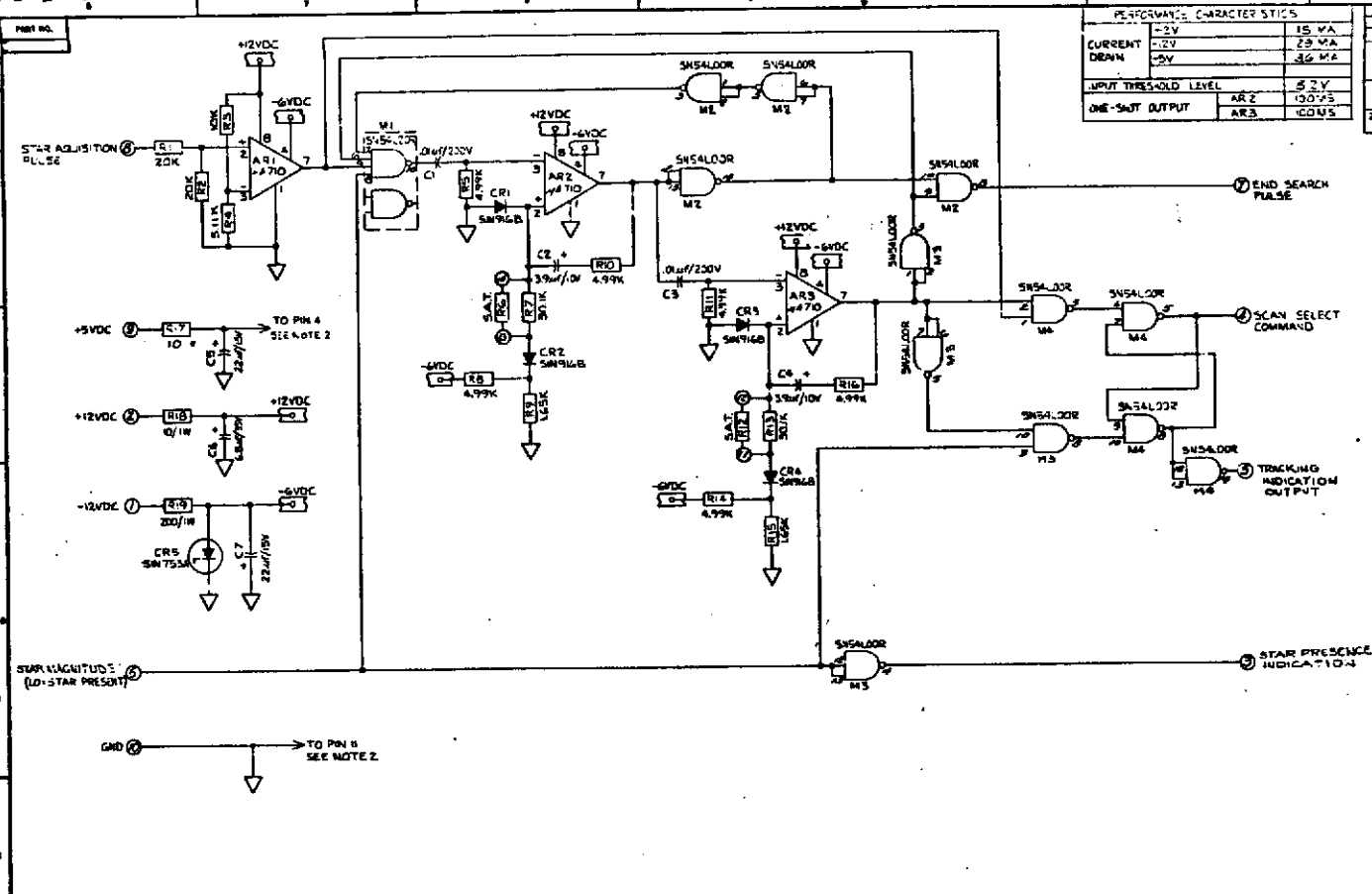
FIGURE 2.4.3-7

FIGURE 2.4.3-8

The Demodulator operates in the following manner. The demodulator gates receive the pulse extender output, process the information, and feed it to the output switches. The supply voltages for the switches come from a special regulated supply in which both voltages track, thereby causing the absolute value of the two voltages to remain the same. The outputs of the switches are summed, filtered, and fed to the output current drivers.

2.4.3.6   Scan Selector

The Scan Selector determines which of the two scans, raster or cruciform, is to be used, and is shown in the schematic of Figure 2.4.3-9.

The threshold detector output is at a high level whenever the Star Acquisition input is above a preset threshold level (7 volts). The threshold detector output triggers one-shot AR2 through the input nand gate provided the gate is not inhibited. If there is a Star Presence signal or if the circuit is already in the "end-search" state, the input gate is inhibited and Star Acquisition pulses do not get through to AR2. The output of one-shot AR2 stays high for approximately 100 ms after it is triggered. When the output switches to low, one-shot AR3 is triggered. When a Star-Acquisition pulse is received while one-shot AR3 is on, the output flip-flop changes stage, providing a signal to switch the system to the cruciform scan (Track) mode of operation. If the Star Presence signal is lost after the oneтshot AR3 output terminates, the output flip-flop switches again, returning the system to the raster scan (Search) mode of operation.

FIGURE 2.4.3-9

2.4.3.7   High Voltage Power Supply

The High-Voltage Power Supply is powered from the +12
volt regulated power supply. The circuit provides a
-2000V output to the 10 megohm resistive divider chain
which supplies the phototube bias. In addition, the
circuit provides the clock pulses for the remainder of
the telescope electronics. The circuit schematic
appears in Figure 2.4.3-10.

Figure 2.4.3-11 is the circuit block diagram. Section
A is the equivalent of the SIN827A reference diode.
Section B is the remainder of the power supply and
regulator. A_2 represents the DC-to-DC converter which
supplies -2000V from a +10V input. The DC-to-DC
converter also supplies the system clock pulses. B is
a voltage divider ratio determined by the load and the
S.A.T. resistors (R10 and R11). A_1 represents the
two 709 amplifiers and the following transistor stage.

The load current returns through R10 and R11 where it
produces a voltage which tends to bring the AR1
amplifier input to ground potential. The voltage at
the AR1 input is the circuit error voltage. AR1
amplifies the error signal and also serves as a high-
input-impedance buffer, drawing very little current
from the high-voltage return. The AR2 amplifier provides
additional gain and frequency compensation to stabilize
the regulator loop. Q4 provides a phase inversion and
drives the control transistor, Q1. Q1 controls the
voltage to the DC-to-DC converter which completes the
regulator loop.

PERFORMANCE CHARACTERISTICS

+12V LINE CURRENT	70 ma
-12V LINE CURRENT	3 ma
OUTPUT VOLTAGE	-2000V
OUTPUT CURRENT	200μA
RIPPLE	5V p-p
PULSE FREQUENCY	3800 HZ
PULSE AMPLITUDE	10V

ELECTROSTATIC SHIELD

NOTES:
1. ALL RESISTORS ARE EXPRESSED IN OHMS AND ARE 1/10 WATT ±1% UNLESS OTHERWISE SPECIFIED.
2. ALL CAPACITORS ARE EXPRESSED IN MICROFARADS UNLESS OTHERWISE SPECIFIED.

SCHEMATIC DIAGRAM,
HIGH VOLTAGE
POWER SUPPLY

19315   2125321

FIGURE 2.4.3-10

V_S = 12 Volt Line Voltage

V_Z = 6.2V, Nominal Zener Reference Voltage

I_Z = 7.5Ma, Nominal Zener Current

R_B = 768Ω Zener Bias Resistor

R_Z = 10 Ω, Zener Dynamic Impedance

A_1 = (21)(-80.7)(-.9) = +1525, DC Gain of the two 709 Amplifiers and the
following Transistor Stage

A_2 = -200, DC to DC Converter Gain (DC)

$\beta = \dfrac{31 \times 10^3}{10.03 \times 10^6}$ = 3.09 x 10^{-3}, Voltage Divider, $\dfrac{R10 + R11}{R_L + R10 + R11}$

FIGURE 2.4.3-11

NOTES:
1. UNLESS OTHERWISE SPECIFIED ALL RESISTOR VALUES ARE GIVEN IN OHMS AND ARE 1/8WATT, ±1%.
2. UNLESS OTHERWISE SPECIFIED ALL CAPACITOR VALUES ARE GIVEN IN MICROFARADS AND THE SECOND FIGURE IS THE VOLTAGE RATING.
3. SELECT AT TEST R4, R17 FROM THE FOLLOWING RESISTORS:

PERFORMANCE CHART

QUIESCENT CURRENT	+28V	
	+12V	
	+5V	
	-12V	
INPUT THRESHOLD		
LOAD	84 Ω + 21 mA	

+28VDC
+12VDC
PROCESSED VIDEO
END SEARCH PULSE
STAR PRESENCE
SHUTTER CLOSED INDICATION
+5VDC
CLOSE SHUTTER COMMAND
+12VDC
ES HI
ES LO
SS LO
SS HI
GND
SHUTTER OPENED INDICATION
UNREG +28+
UNREG RETURN

PROCESSED VIDEO OUTPUT
END SEARCH PULSE
STAR PRESENCE INDICATION
SHUTTER CLOSED OUTPUT
SHUTTER ENERGIZED

SHUTTER MOTOR

REVISIONS

THE BENDIX CORPORATION

ELECTRICAL SCHEMATIC SHUTTER, ELECTRICAL

F 19315 2125371

FIGURE 2.4.3-12

High loop gain minimizes output changes due to gain and offset variations. The high gain of A_1 minimizes output changes due to line voltage variations. CR7 is a temperature compensated reference diode which provides a stable reference voltage.

2.4.3.8   Shutter Electronics

The Shutter Electronics receives command inputs from the Earth and Sun Sensors, and from the Mode Selector, and appropriately controls the shutter. A schematic of the Shutter Electronics is shown in Figure 2.4.3-12.

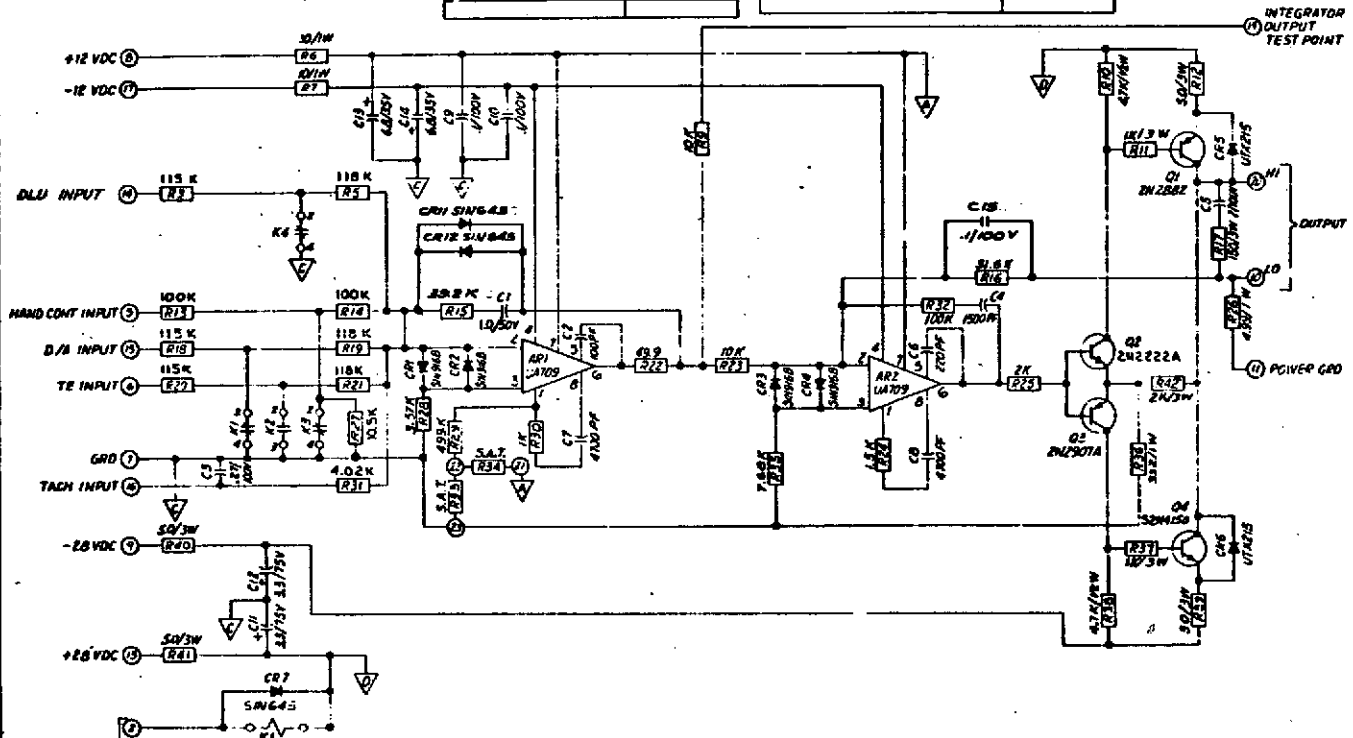2.4.4   Servo Electronics

2.4.4.1   General Description

The servo electronics consist of a dual-channel servo amplifier to provide drive signals to the Star Tracker's gimbal torque motors, and of switching circuits to enable the system modes of operation: Track, Hold, Search and Manual. A schematic of the servo amplifier along with the switching relays, is shown in Figures 2.4.4-1 and 2.4.4-2 for the inner gimbal and outer gimbal, respectively. Each amplifier channel is seen to consist of an operational amplifier to provide the necessary compensation and voltage gain, and a power amplifier to provide the power gain required to drive the gimbal DC torque motors.

The servo amplifier is designed to operate in four modes of operation: Track, Hold, Manual and Search. In the Track mode the servo amplifiers receive analog error signals from the telescope electronics and convert them to command signals for the appropriate gimbal torquers.

FIGURE 2.4.4-1

FIGURE 2.4.4-2

In the Hold mode the servo amplifier receives error
signals from the D/A converters located in the Digital
Logic Unit (DLU). These error signals are proportional
to the difference between the commanded "hold" positions
and the actual gimbal positions (as indicated by the
optical encoders), and the servo amplifier drives the
gimbal torquers so as to reduce the errors to zero.

In manual operation, the astronaut's hand controller
is connected directly to the rate-loop inputs of
both channels. In search operation, the inner gimbal
amplifier receives an error signal from the D/A Con-
verter which is proportional to the difference between
the programmed search angle and the actual inner-gimbal
angle. This error signal is driven to zero by appropri-
ately driving the inner-gimbal torque motor. The outer-
gimbal amplifier, in the search mode, accepts an analog
signal directly into its rate loop. This signal is
controlled by the DLU in accordance with the programmed
search pattern, and is scaled to produce a gimbal rate
of one deg/sec.

2.4.5   Digital Logic Unit

The Digital Logic Unit (DLU) contains the electronics
required to perform a fine and coarse two-axis gimbal
search, and the electronics required to hold the
gimbals in a fixed position. In addition, the DLU
provides the ATM Digital Computer, the Control and
Display Panel, and Telemetry with inner and outer
gimbal position information.

In particular, the DLU performs the following operations:

1. Holds the Star Tracker gimbals in their last posi-
    tion when a "Hold" command is received from the
    ATM/Tracker interface circuitry.

2. Conducts a fine and coarse two-axis gimbal search
    when a "Search" command is received from the
    ATM/Tracker interface circuitry.

3. Supplies the ATM Digital Computer with inner and
    outer gimbal position information, in serial binary
    form, (MSB first), upon command.

4. Supplies the Control and Display Panel with inner
    and outer gimbal position information in parallel
    binary-coded-decimal form.

5. Supplies Telemetry with inner and outer gimbal
    position information in parallel binary form.

A simplified block diagram showing the DLU/Servo Loop
configurations for the Hold and Search modes of operation
is shown in Figure 2.4.5-1. In the Hold mode the inner
and outer gimbal loops are identical. In operation the
initial gimbal positions are stored and from them are
subtracted the actual gimbal positions which are obtained
from the gimbal mounted digital encoders. The resulting
digital error signals are stored in the "Error Storage
Registers" and are converted to DC analog signals by the
"D/A Converters". These signals are fed to the Star
Tracker's gimbal electronics which drive the error
signals to null.

In the Search mode, the inner and outer gimbal loops
have different configurations. Reference to Figure
2.4.5-1 shows that the outer gimbal search motion is
achieved by driving the outer gimbal rate loop at a

① INNER AND OUTER GIMBAL LOOP
CONFIGURATION DURING HOLD

	MF		REVISIONS		
		SYM	DESCRIPTION	DATE	APPROVAL

INITIAL POSITION REGISTER → SUBTRACTOR → ERROR STORAGE REGISTER → D/A CONVERTER → STAR TRACKER POSITION LOOP ELECTRONICS → GIMBAL

ENCODER

② INNER GIMBAL LOOP CONFIGURATION DURING SEARCH

PROGRAM CONTROL
+ 3/4°   - 3/4°

NULL DETECTOR

INNER GIMBAL INITIAL POSITION REGISTER → SUBTRACTOR → ERROR STORAGE REGISTER → D/A CONVERTER → STAR TRACKER INNER GIMBAL POSITION LOOP ELECTRONICS → INNER GIMBAL

ENCODER

③ OUTER GIMBAL LOOP CONFIGURATION DURING SEARCH

ERROR DETECTOR
DETECT ±.15° COARSE SEARCH
DETECT ± 2° FINE SEARCH

+V   -V   "ZERO RATE COMMAND"

OUTER GIMBAL INITIAL POSITION REGISTER → SUBTRACTOR → ERROR STORAGE REGISTER → DIGITAL SWITCHES → STAR TRACKER OUTER GIMBAL RATE LOOP ELECTRONICS → OUTER GIMBAL

ENCODER

FIGURE 2.4.5-1

THE Bendix CORPORATION

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TETERBORO, NEW JERSEY, U.S.A.

CODE IDENT NO.	SIZE	DLU BLOCK DIAGRAM (SIMPLIFIED)
19315	B	
SCALE	WT	SHEET

constant speed. At the start of the search operation
the outer gimbal position is stored in the "Outer
Gimbal Initial Position Register", and thereafter the
new outer gimbal position is subtracted from it. The
results of the subtraction are stored in the "Error
Storage Register" and are examined by the "Error Detector"
which determines when the extremities of the search
pattern have been reached. When this occurs the drive
signal is removed from the outer gimbal rate loop and
inner gimbal motion is initiated.

The inner gimbal servo loop configuration during the
Search mode is the same as in the Hold mode, with the
exception that the "Initial Position Register" word is
periodically incrmented in $\pm 3/4$ degree steps. In
addition, a "Null Detector" has been added to determine
when the inner gimbal has reached the newly commanded
position. At this time, inner gimbal motion ceases and
outer gimbal motion is resumed.

Search Pattern Description
When the Search Command is received from the Mode
Selector, the DLU electronics cause the gimbal search
pattern shown in Figure 2.4.5-2 to be generated. Examina-
tion of this figure shows the two-axis search to be
conducted in two modes: a fine mode (dashed lines) in
which a ± 2.5 degree by ± 2 degree area, centered about
the starting position, is searched, followed by a
coarse mode in which an angle of $+15.5$ degrees about the
outer gimbal starting position and $+5.75$ and -4.75 degrees
about the inner gimbal starting position is searched.
After the coarse search is ended, the inner gimbal is
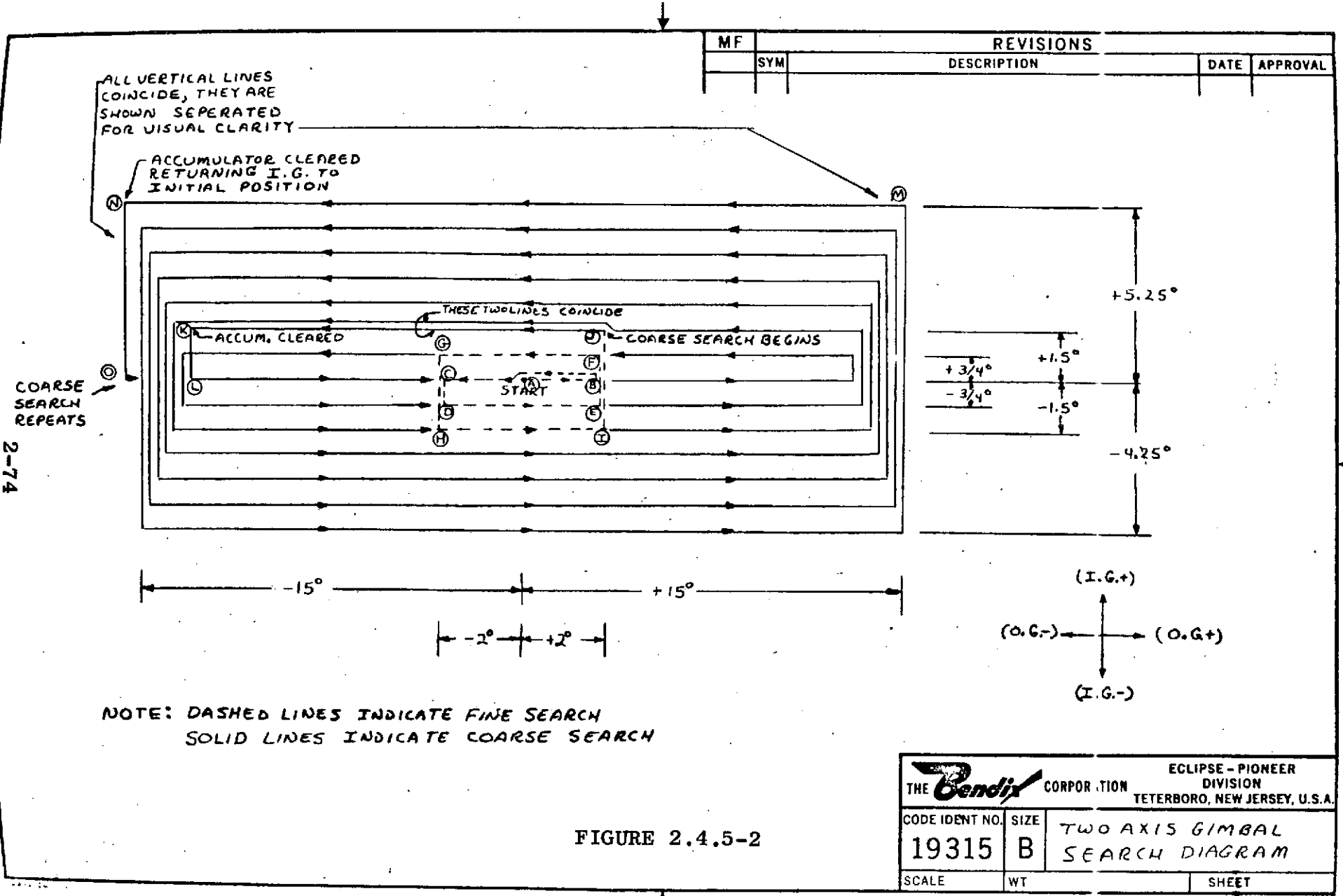
ALL VERTICAL LINES
COINCIDE, THEY ARE
SHOWN SEPERATED
FOR VISUAL CLARITY

ACCUMULATOR CLEARED
RETURNING I.G. TO
INITIAL POSITION

Ⓝ

Ⓜ

COARSE
SEARCH
REPEATS

◎

THESE TWO LINES COINCIDE

Ⓚ ACCUM. CLEARED

Ⓖ

Ⓓ COARSE SEARCH BEGINS

Ⓕ

Ⓒ

Ⓐ
START

Ⓑ

Ⓛ

Ⓙ

Ⓔ

Ⓗ

Ⓘ

+5.25°

+1.5°

+3/4°

-3/4°

-1.5°

-4.25°

$\longleftarrow$ -15° $\longrightarrow$ $\longleftarrow$ +15° $\longrightarrow$

-2° +2°

(I.G.+)

(O.G.-) (O.G.+)

(I.G.-)

NOTE: DASHED LINES INDICATE FINE SEARCH
SOLID LINES INDICATE COARSE SEARCH

FIGURE 2.4.5-2

2-74

THE *Bendix* CORPORATION	ECLIPSE - PIONEER DIVISION TETERBORO, NEW JERSEY, U.S.A.
CODE IDENT NO. **19315**	SIZE **B**	TWO AXIS GIMBAL SEARCH DIAGRAM
SCALE	WT	SHEET

returned to its initial position and the coarse search pattern only is repeated.

The general sweep pattern is achieved by rotating the outer gimbal at a fixed rate, while holding the inner gimbal, and then holding the outer gimbal while indexing the inner gimbal by a multiple of $\pm 3/4$ degree. Thus, the search pattern is characterized by a series of 4 degree or 30 degree sweeps around the outer gimbal axis with each sweep being separated by 3/4 degree of inner gimbal motion. Since the acquisition field-of-view of the telescope is one degree, the star will always be found during one of the outer gimbal sweeps, and hence, the outer gimbal sweep speed should be as uniform as possible. To accomplish this, the outer gimbal is driven by a one deg/sec command applied directly to its rate loop, with the gimbal encoder being used only to determine when the proper angle (± 2 degrees or ± 15 degrees from the initial angle) has been reached. The inner gimbal is indexed the required 3/4 degree angle by means of its position loop, since uniformity of speed is unimportant along this axis.

Block Diagram Description
A simplified block diagram of the Digital Logic Unit is shown in Figure 2.4.5-3. A brief description of each block appearing in Figure 2.4.5-3 follows.

Block No. 1 Clock
The Clock unit generates the basic 10 KHz square wave signal required by the Programmer (Block 2).
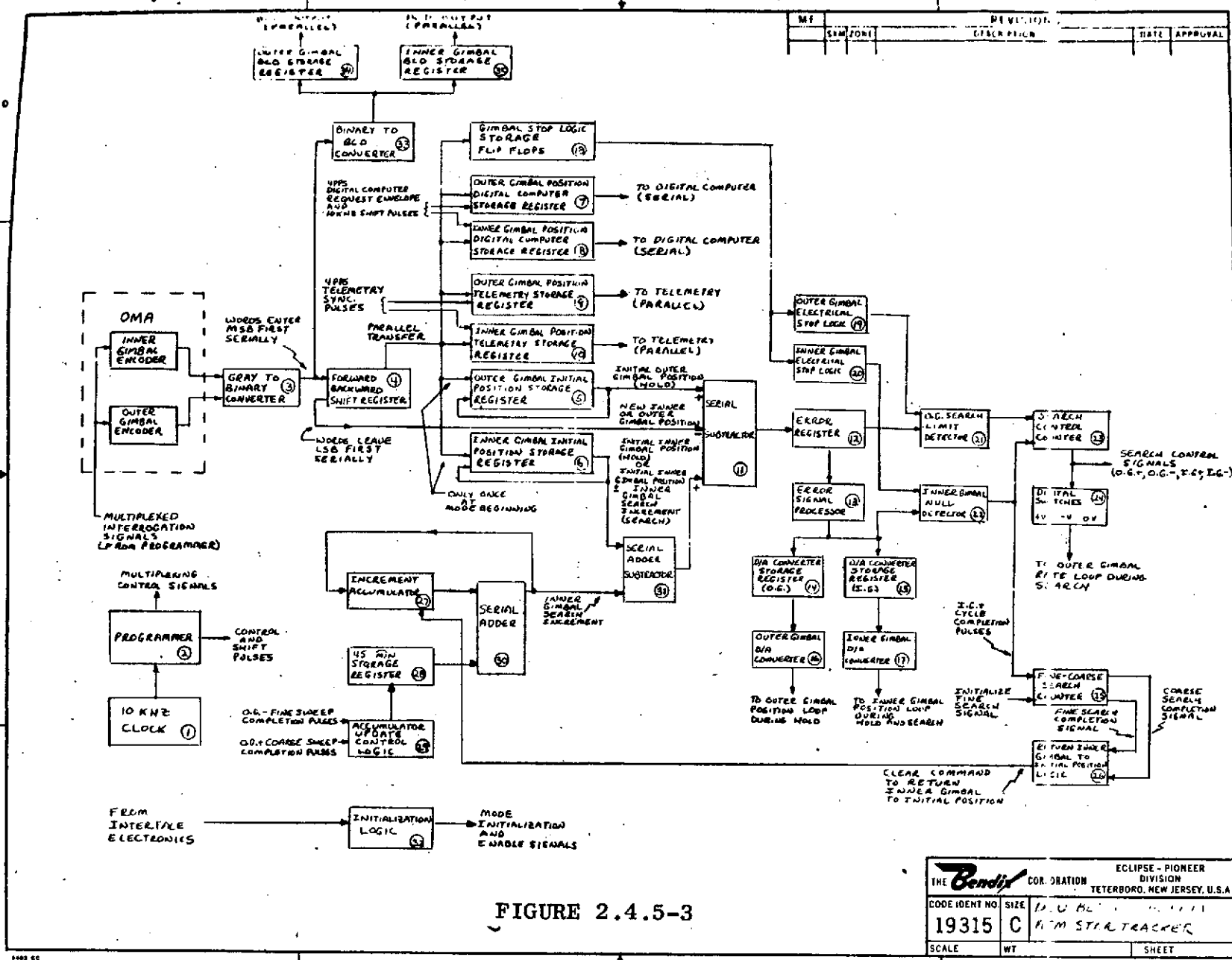
FIGURE 2.4.5-3

Block No. 2 Programmer

The Programmer unit generates the time-multiplexing
envelopes, individual timing pulses, and 10 KHz
shift-pulse bursts required to control the sequential
operation of the DLU. The unit itself consists of a
five-stage synchronous Gray-code counter designed to
divide by a factor of 22, a cascaded two-stage synchronous
Gray-code counter designed to divide by a factor of
four, and associated gating circuitry. Each program
cycle thus consists of 88 cycles of the 10 KHz clock.

Block 3 Gray to Binary Converter

The Gray-to-Binary Converter converts the multiplexed
serial Gray-coded outputs of the gimbal encoders, MSB
first, to a serial binary word. The converter implements
a common Gray-to-Binary conversion rule whereby the most
significant binary digit is the same as the corresponding
Gray-code digit, and each successive binary digit is
complemented if the corresponding Gray-code digit is
a "1" or is left as is if the corresponding Gray-code
digit is a zero.

Block No. 4 Forward-Backward Shift Register

The Forward-Backward Shift Register accepts binary-
coded serial information from the Gray-to-Binary
Converter (Block 2), MSB first, stores the information
for a time, and then shifts it, LSB first, through the
Subtractor unit of Block 11. During the interval in
which the word is stored, it is parallel transferred
to the Digital Computer and Telemetry Storage Registers
(Blocks 7-10), to the Gimbal Stop-Logic, Storage Flip-
Flops (Block 18) and, at the start of a Search or Hold

operation, to the Inner and Outer Gimbal Initial
Position Registers (Blocks 5,6).

Block No. 5, 6   Initial Position Storage Registers
The Initial Position Storage Registers store the gimbal
positions which are present at the start of a Hold
or Search operation. These registers are thus updated
only when a Hold or Search operation is first initiated;
and, thereafter the contents of these registers serve as
the reference angles required in the Hold and Search
modes. When the Initial Position Registers are updated,
the new information is received from the Forward Backward
Shift Register, Block 4, in parallel form. The output of
each of the Initial Position Registers is serial, and
depending on the mode of operation, is passed through
one of the subtractor units (Blocks 11, 31).

Blocks Nos. 7, 8 Digital Computer Storage Registers
The Digital Computer Storage Registers receive new
gimbal position information once each program cycle, in
parallel form, from the Forward-Backward Shift Register
(Block 4). This information is then read out asynchronously
by the Digital Computer, in serial form, at a rate of
four 10 KHz readouts per second. Suitable gating is
provided to prevent the storage registers from being
updated during the time in which the information is
being serially transferred to the Digital Computer.

Blocks 9, 10 Telemetry Storage Registers
The Telemetry Storage Registers are updated by a parallel
transfer of information from the Forward-Backward Register
at a rate of four updates per second. Each update is
initiated by a 4 pps 278 μsec sync pulse from telemetry,

and the information words are made available to telemetry
in a parallel format.

Block 11   Serial Subtractor

The Serial Subtractor unit of Block 11 subtracts the most
recent encoder position word, received serially from the
Forward-Backward Shift Register (Block 4), from the
commanded position word. The commanded position word
is the initial position, (obtained serially from the
Initial Position Registers, Blocks 5,6), when the system
is in the Hold mode of operation. When the system is in
the Search mode, the commanded position word is the
initial position for the outer gimbal portion of the
program cycle, and is the initial position plus or minus
a predetermined angle increment (generated by Blocks 27-31)
for the inner gimbal portion of the program cycle.

Block 12   Error Register

The Error Register receives, in serial form, the results
of the subtraction performed by the Subtractor unit of
Block 11, and stores the error word.

Block 13   Error Signal Processor

The Error Signal Processor examines the 15-bit word in
The Error Register (Block 12) for sign, and for magni-
tude in excess of the D/A Converter's $\pm$64 increment
output swing, and appropriately sets the 7-bit D/A
Converter Storage Registers (Blocks 14, 15). The
Processor thus operates on the 15-bit word in the Error
Register to produce a 7-bit word (1 sign bit and 6 magni-
tude bits) which is subsequently stored in one of the D/A
Converter Storage Registers. This 7-bit word has the

following characteristics:

a. The MSB (i.e. the sign bit) is the same as the MSB
    of the unprocessed error word.

b. For non-saturated errors (i.e. errors smaller in
    magnitude than 64 increments), the remaining 6 bits are
    the same as the last 6 bits of the unprocessed word.

c. For saturated errors of positive polarity (+64
    increments or larger) the remaining 6 bits are all
    "logical ones".

d. For saturated errors of negative polarity (-64
    increments or smaller) the remaining 6 bits are all
    "logical zeros".

Blocks 14, 15 D/A Converter Storage Registers

The D/A Converter Storage Registers store the processed
error signals and make them available to the D/A
Converters on a continuous basis. These registers
accept multiplexed parallel inputs from the Error Signal
Processor (Block 13) and send parallel outputs to the
D/A Converters.

Blocks 16, 17 D/A Converters

The D/A Converters convert the processed digital error
signals to analog voltage signals which are used to
drive the gimbal servo loops. Each D/A Converter unit
consists of a microcircuit operational amplifier with
an associated binary-weighted-resistor input network.

Block 18 Gimbal Stop Logic Storage Flip Flops

The Gimbal Stop Logic Storage Flip-Flops store the seven
most significant bits of the gimbal readout angle. The
outputs of these flip-flops are sent to the Gimbal Stop
Logic Electronics (Blocks 19, 20).

Block 19 Outer Gimbal Stop Logic

The Outer Gimbal Stop Logic detects when the outer
gimbal angle reaches $+87.467^O$ or -87.475^O. When either
of these angles are reached a signal is sent to the
Search Limit Detector, (Block 21) terminating the
outer gimbal sweep and initiating the next I.G.
incrementation.

Block 20 - Inner Gimbal Stop Logic

The Inner Gimbal Stop Logic detects when the inner
gimbal angle reaches +40.533 degrees or -40.54 degrees.
When either of these angles are reached a signal is sent
to the Inner Gimbal Null Detector, (Block 22), termi-
nating the inner gimbal motion and initiating the next
outer gimbal sweep.

Block 21 - Outer Gimbal Search Limit Detector

The Outer Gimbal Search Limit Detector is used in the
Search mode to determine when the limits of the required
outer-gimbal motion have been reached. In the Fine
Search mode these limits are set at +2.0 degrees and
-2.0083 degrees from the initial position, and in the
Coarse Search mode these limits are set at +15.0
degrees and -15.0083 degrees from the initial position.
When these limits have been reached a signal is
generated which is used to advance the Search Control
Counter (Block 23).

Block 22 Inner Gimbal Null Detector

The Inner Gimbal Null Detector is used in the Search
mode to determine when the inner gimbal has completed
its travel to a newly commanded position. When the

inner gimbal comes within   1.5 arc min. of the commanded
position the Null Detector produces an output signal
which is used to advance the state of the Search
Control Counter (Block 23).

Block 23   Search Control Counter
The Search Control Counter is used in the Search mode
to determine which gimbal is to be rotated and in which
direction.   The sequence of gimbal motion, as commanded
by this counter, is: OG (+)   IG (+)   OG (-)
IG (-)   OG (+)...

The counter itself is a two stage synchronous Gray
counter and it is advanced each time a signal is
received from the Outer Gimbal Search Limit Detector,
or the Inner Gimbal Null Detector.

Block 24   Digital Switches
The Digital Switches insert a positive drive command,
a negative drive command, or a zero drive command,
into the outer-gimbal rate loop during the Search
mode of operation.   The positive drive signal is
inserted when the Search Control Counter (Block 23)
commands OG (+), the negative drive signal when OG (-),
is commanded, and the zero drive signal when IG (+)
or IG (-) is commanded.

Block 25   Fine/Coarse Search Counter
The Fine/Coarse Search Counter is used to determine
when the fine gimbal search is completed and when the
coarse gimbal search is completed.   The counter itself
consists of a three stage synchronous binary counter

which counts the number of IG (+) weeeps. When
2 IG (+) sweeps have been counted the fine search
ends, the inner gimbal is returned to its initial
position and the coarse search begins. When 7
additional IG (+) sweeps have been counted the coarse
search ends, the inner gimbal is returned to its
initial position, and the coarse search repeats.

Block 26   Return LG to Initial Position
The Return Inner Gimbal to Initial Position logic
receives fine and coarse search completion signals
from the Fine/Coarse Search Counter (Block 25), and
in response, issues a signal which clears the
Increment Accumulator (Block 27). This results in the
inner gimbal being returned to its initial position,
which allows the next search pattern to be started.

Block 27   Increment Accumulator
The Increment Accumulator contains the commanded angle,
relative to the initial inner gimbal angle, to which
the inner gimbal is to be positioned during the Search
mode. This angle is generated by adding 45 arc minute
increments to the original Accumulator number (initially
zero) each time the inner gimbal is to be moved a new
distance from the starting point. This addition is made
each time an OG (-) sweep is completed when the coarse
search is in progress, and is controlled by the
Accumulator Update Control Logic (Block 29).

Block 28   45 Arc Minute Storage Register
The 45 Arc Minute Storage Register stores a digital
word with a weight of 45 arc minutes. This number is

added to the Increment Accumulator (Block 27) at the
appropriate time as determined by the Accumulator
Update Control Logic (Block 29).

Block 29   Accumulator Update Control Logic
The Accumulator Update Control Logic causes 45 arc
minute increments to be added to the Increment
Accumulator (Block 27) each time the inner gimbal
is to be moved a new distance from its starting
point.   This addition is caused to occur each time
an OG (-) sweep is completed when the fine search
is in progress, and each time an OG (+) sweep is
completed when the coarse search is in progress.

Block 30   Serial Adder
The Serial Adder of Block 30 performs the addition in
which 45 arc minute increments are added to the con-
tents of the Increment Accumulator (Block 27).   The
results of the addition are stored in the Increment
Accumulator.

Block 31   Serial Adder/Subtractor
The Adder Subtractor Unit adds (or subtracts) the
contents of the Increment Accumulator (Block 27) to
(from) the contents of the Inner Gimbal Initial
Position Register (Block 6).   The result of this
addition (or subtraction) is the angle to which the
inner gimbal is commanded during the search mode.
The addition operation takes place when and IG (+) or
OG (-) sweep is in progress, and the subtraction takes
place when an IG (-) or OG (+) sweep is in progress.

Block 32   Initialization Logic

The Initialization Logic detects when a Hold or Search
operation is first commanded and appropriately prepares
the DLU to perform the desired operation. In particular,
at the start of both modes, the Initial Position Registers
(Blocks 5,6) are updated. In addition, at the start of
the Search mode, the Search Control Counter (Block 23)
is cleared, the Increment Accumulator (Block 27) is
cleared, and the Fine/Coarse Search Counter (Block 25)
is cleared and set to implement the fine search.

Block 33   Binary to BCD Converter

The Binary-to-BCD Converter is used to convert the
serial binary-coded gimbal position information,
available at the output of the Gray-to-Binary Converter
(Block 3), into binary-coded decimal form with a
resolution of 1.0 arc minute. The actual output of the
Converter consists of sign information in the form of
two 28 volt discretes, and magnitude information in
the form of a four-digit binary-coded-decimal number.

The binary-to-BCD conversion is accomplished by shifting
the binary number, most-significant bit first, into a
specially-gated shift register which counts in BCD
form. If the binary number is negative it is complemented
before being passed through the converter.

Blocks 34, 35   BCD Storage Registers

The BCD Storage Registers store the inner and outer gimbal
binary-coded decimal words and make them available to the
PCS Control and Display Panel on a continuous basis.

2.4.6   Power Supplies

2.4.6.1   Encoder Power Supply (+1.45 VDC)

The 1.45 VDC supply drives the encoder lamps, whose
intensity must be accurately controlled. A schematic
of this supply is shown in Figure 2.4.6-1, and switching
regulation techniques are used because of the high power
loss inherent in series regulation at this low voltage
level. In response to load or input line variations,
the duty cycle of the pulses from the power switch to
the transformer is varied to maintain the output constant.

In operation, the output voltage is compared at Q10 with
a fractional part of the reference voltage from CR12.
The difference voltage is amplified by Q10, Q8, Q9 and
Q11, causing the collector voltage of Q11 to vary as a
function of the output voltage. Since the timing network
C11 and R13 is connected to Q11, the cutoff time of
multivibrator transistor Q6 also varies as the output
voltage. The on time remains fixed at 17 microseconds
since R11 is returned to a fixed voltage.

Thermistor RT5 compensates for changes in output voltage
due to temperature variations by adjusting the reference
voltage. RT4 compensates for beta changes of Q11 due to
temperature variations by adjusting the drive to Q11.
R37, C19, C20 prevent oscillation of linear amplifier
Q11.

Q2 serves a threefold purpose of isolating the multi-
vibrator from the following stages, supplying bias to the
timing networks, and providing positive-starting of the
multivibrator.

FIGURE 2.4.6-1

NOTES:
1. ALL RESISTORS ARE EXPRESSED IN OHMS ±1% AND ARE 1/8 WATT, UNLESS OTHERWISE SPECIFIED.
2. ALL CAPACITORS ARE EXPRESSED IN MICROFARADS ±10% AND 200V, UNLESS OTHERWISE SPECIFIED.
3. SELECT AT TEST R1 FROM THE FOLLOWING RESISTORS: 2125411-7 (2.21), -11 (2.26), -13 (2.32), -15 (2.376)(17 (2.43), -21 (1.74), -23 (2.6)
4. C10 & C11 MUST HAVE 8X CHARACTERISTIC.
5. SELECT AT TEST R32 FROM THE FOLLOWING RESISTORS: 1855931-169 (121K), -191 (71.5 K), -57 (54.9K), -116 (48.7K), -149 (35.7K), -269 (32.4K), -51 (26.7K), -270 (23.2K), -88 (20.5K), -133 (18.7K) & -131 (17.4K).

ELECTRICAL SCHEMATIC
POWER SUPPLY
1.45 VDC

F | 19315 | 2125751

Q4 inverts the oscillator pulse to drive power switch
Q7. Q3 turns off as the pulse goes in the negative
direction, thereby increasing efficiency. RT2 and
RT3 provide increased drive at low temperatures to
offset loss of beta. Q7 alternately pulses primary
of T1 on and off with a duty cycle proportional to
the output voltage. The secondary voltage swings
around an average value determined by the duty cycle,
and is rectified, filtered, and supplied to the load.

2.4.6.2   DC Power Supplies

The DC power supplies produce the regulator ± 12 VDC,
and +5VDC voltages required by the system. These
supplies are conventional in design and are shown in
Figures 2.4.6-2, 2.4.6-3 and 2.4.6-4.

PERFORMANCE CHARACTERISTICS	
INPUT VOLTAGE	+22VDC TO +32/DC
OUTPUT VOLTAGE	+12VDC ±1%
INPUT CURRENT @ 28V	155MA
LOAD CURRENT @ 38.1 Ω	325MA
RIPPLE	3MV P-P
EFFICIENCY	85%
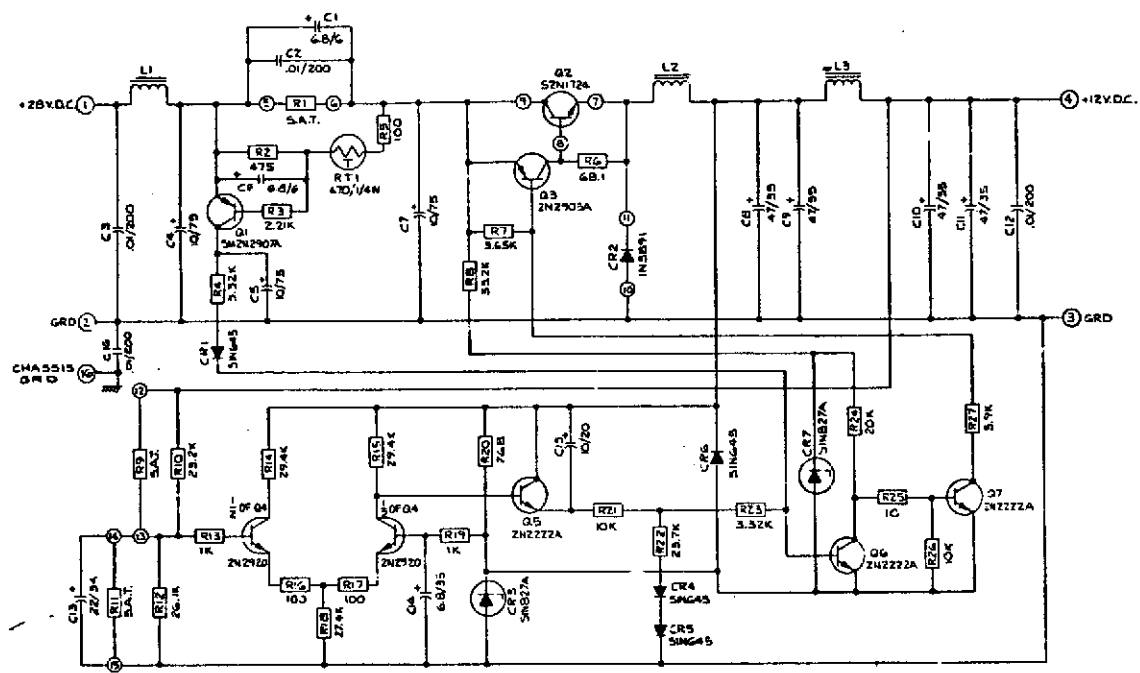
NOTES:
1. ALL RESISTOR VALUES ARE IN OHMS AND ARE ±1%, 1/8 WATT RATING UNLESS OTHERWISE SPECIFIED.

2. ALL CAPACITOR VALUES ARE IN MICROFARADS ±10% AND THE SECOND FIGURE INDICATES VOLTAGE.

3. SELECT AT TEST R FROM THE FOLLOWING 2125411 TYPE RESISTORS: -21(1.74Ω),-23(2.2Ω),-25(2.49Ω),-5(3.01Ω)

4. SELECT AT TEST R9 FROM THE FOLLOWING 155931 TYPE RESISTORS: -88(20.5Ω),-90(21.0Ω),-144(21.5Ω),-50(22.1K),-198(22.6K),-273(23.2K), -202(23.7K),-145(24.2Ω),-28(24.9K),-122(25.5K),-288(26.1K).

5. SELECT AT TEST RII FROM THE FOLLOWING 155931 TYPE RESISTORS: -202(23.7K),-145(24.3K),-28(24.9K),-122(25.5K,-288(26.1K), -51(26.7K),-185(27.4K),-145(28.0Ω),-255(28.7K).

ELECTRICAL SCHEMATIC POWER SUPPLY +12V.D.C.

SIZE F	CODE IDENT NO. 19315	2125781

FIGURE 2.4.6-2

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FIGURE 2.4.6-3

FIGURE 2.4.6-3

120

2.5 MECHANICAL DESIGN

2.5.1 DESIGN PHILOSOPHY

In view of the large temperature range to which the OMA
is subjected, as well as launch shock and vibration, the
mechanical design has been aimed at developing maximum
mechanical stability. First, it may be seen that
structural symmetry has been employed widely. Also,
materials with similar coefficients of expansion are
used throughout. Truss rib designs were chosen to
afford maximum resistance to deflection, and gimbal
pivot bearings have been configured to contribute to
maximum gimbal rigidity. Improved stability through
the folded optical path has been realized through the
use of a pair of wedge reflecting mirrors which are
rotated for adjustment and securely locked in position.
The design philosophy of each element will be discussed
in the description of each subassembly.

2.5.2 STRUCTURAL CONSIDERATIONS

In order to provide a light-weight alloy of moderate cost
with a coefficient of expansion matching stainless
steel, (about 8.4×10^{-6} in/in/$^{\circ}$F), a vanadium-aluminum-
silicon casting alloy was selected for the frame, gimbal,
and telescope housing. This alloy, Reynolds A-390 is termed
hyper-eutectic in that it contains 19 percent silicone,
12 percent in solution and the remainder distributed
throughout the matrix. Its unusual stability is traded
for somewhat difficult machinability and reduced tensile
properties. The cross-ribbed pattern employed in the
frame and gimbal affords a marked increase in resistance
to structural deflection over that of other candidate

rib patterns. This is particularly useful as in this case where a three-point mount in a plane below the c.g. is called upon to survive launch loads and resist deformation.

Each raw casting is solution heat-treated at 900^OF and artifically aged at 350^OF to develop maximum properties. Each part is penetrant inspected and x-rayed to assure integrity. Before final machining, stability is improved by subjecting the part to a number of cycles wherein it is alternately heated and chilled over the expected temperature range.

The particular stainless alloy which matches the coefficient of expansion of Vanasil is grade 309, one of the less common grades of 18-8. It is used rather widely throughout the tracker.

To afford maximum gimbal rigidity and avoid sliding fit hangup, both bearing pairs in both gimbal pivots are securely preloaded and neither is floated. This only becomes feasible with a close match of coefficients as described.

2.5.3 DESCRIPTION OF MECHANICAL DETAILS

A modular concept has been followed throughout the OMA design. Major elements in the assembly consist of the frame, gimbal, inner and outer torquer pivots, inner and outer encoders and pivots, and the telescope assembly.

2.5.3.1   FRAME

The Frame is the structural chassis which supports the
entire tracker and by which the assembly is mounted
on the vehicle rack. The frame pivot bores are line-
bored accurately with respect to the plane of the
mounting feet and also the pad which receives an align-
ment reference mirror. The hole pattern in the bushed
mounting feet is transferred to the feet by means of
a drill jig fixture which has been precisely positioned
with respect to the pivot axis by clamping against an
alignment bar and lateral locating pin. Holes in the
spacecraft support rack are transfer-drilled from an
identical fixture. Mounting bosses for an elapsed time
indicator, gimbal stop, and nameplate are provided in
the machined casting, Figure 2.5.3.1-1.

2.5.3.2   GIMBAL

Materials and construction of the gimbal is similar to
that of the frame. Pivot bores are held to a high
degree of orthogonality to benefit pointing accuracy.
The upper and lower flanges are machined to receive
pairs of covers which serve the primary purpose of
thermal control but also afford structural support to
the gimbal. As for the gimbal as well as the frame,
bores and tapped holes are provided with liners and
inserts. In the majority of cases, threaded inserts
are of the helical coil type and commonly include a
deformed-coil self-locking feature to secure mating
screws. Figure 2.5.3.2-1 depicts a completed gimbal.
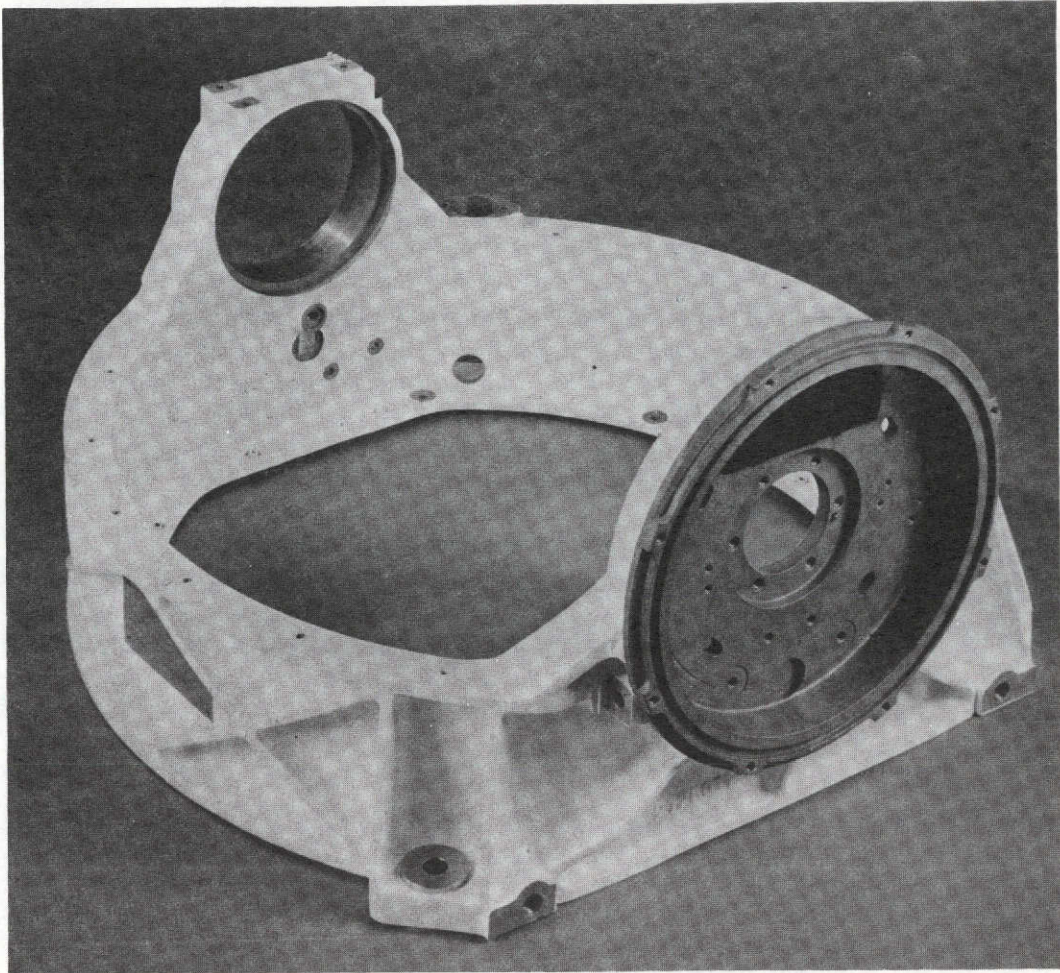
FRAME MACHINED — ENCODER END
2125010-1
FIGURE 2.5.3.1-1
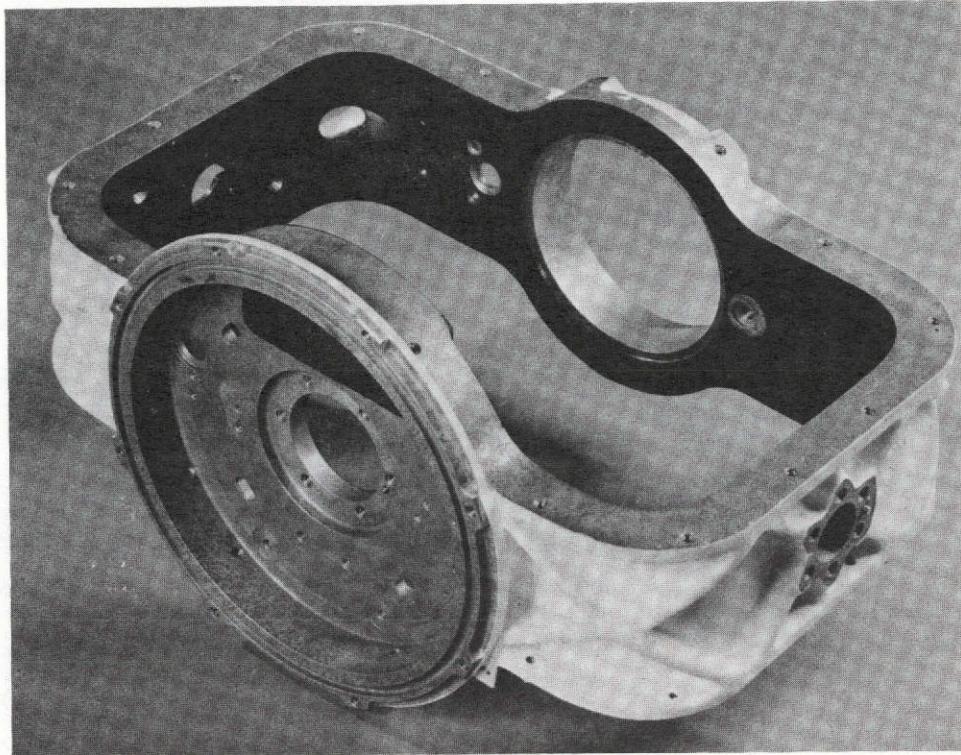
GIMBAL MACHINED – ENCODER END
2125051-1
FIGURE 2.5.3.2-1

2.5.3.3   TELESCOPE HOUSING

Adhering to the principle of uniform materials, the
telescope housing is also constructed of A-390.
Resembling a cluster of three cylindrical elements,
the three bores of the housing contain the lens assembly,
photomultiplier tube, and high-voltage power supply,
respectively, Figure 2.5.3.3-1.

2.5.3.4   OPTICS

The lens assembly consists of a coated aplanatic air-
spaced doublet lens mounted within a tube assembly
which is threaded to afford initial focusing. A pair
of aluminized and coated metal wedge mirrors fold the
optical path 180 degrees. These mirrors are rotated to
position the focal point in the center of the Cathode
target. Geometric symmetry and close matching of
materials properties combine with careful design to
insure a very stable optical system which is insensitive
to environmental changes.

2.5.3.5   PHOTOTUBE

The photomultiplier tube assembly consists of the tube
proper, a toroidal magnetic sweep yoke, and an external
set of nested shielding cans. The high voltage photo-
cathode lead resides within a tunnel in the shield and
the entire assembly is potted by a vacuum process which
assures elimination of internal voids which contribute
to arcing problems. Locating the high voltage power
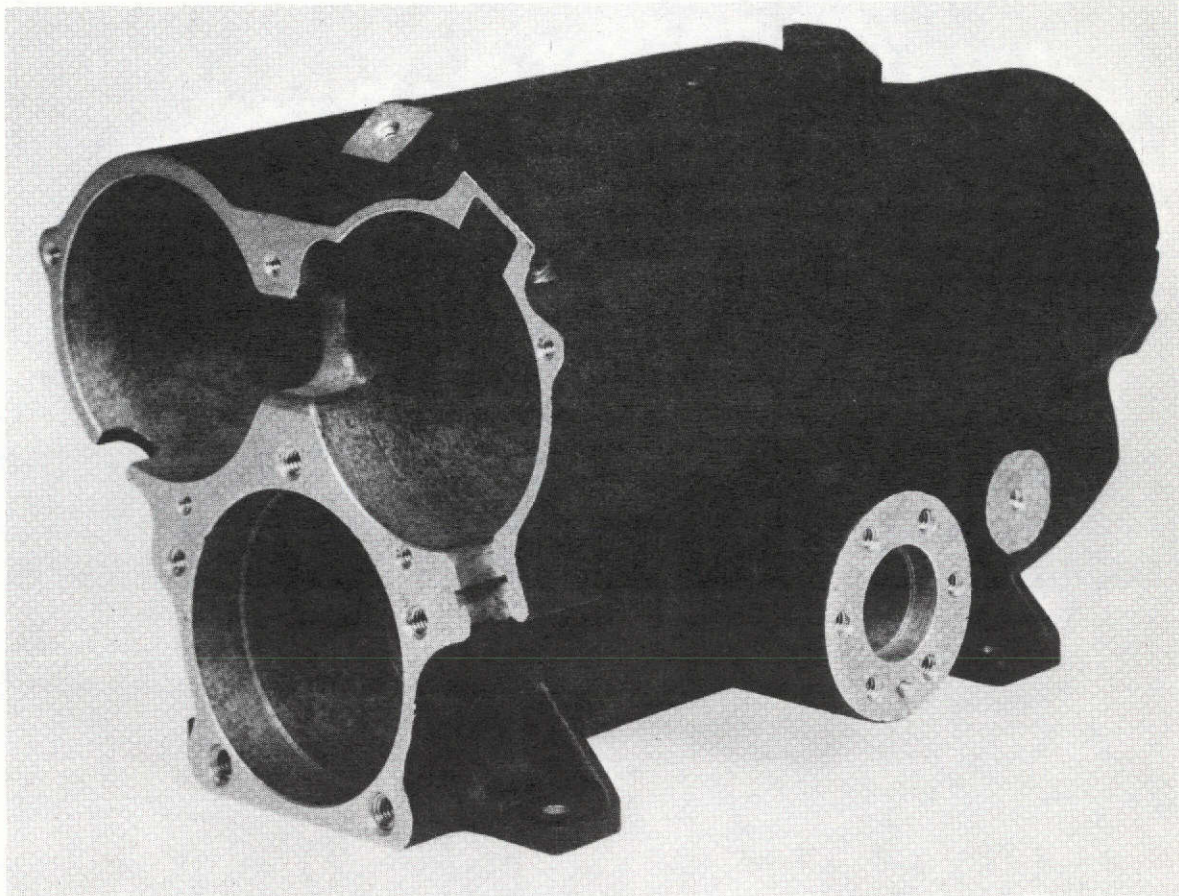
TELESCOPE HOUSING
FIGURE 2.5.3.3-1

supply adjacent to the tube assembly minimizes lead
length for this same purpose.

2.5.3.6   ELECTRONICS

Processing signal circuitry and shutter control logic
is packaged in a modular Telescope Electronics Assembly
attached to the telescope housing by means of four screws.
Two connector plugs facilitate installation, Figure
2.5.3.6-1. The unit consists of an array of printed
circuit component boards contained within an aluminum
housing. In addition to shutter command circuitry, the
assembly contains the video amplifier, scan selector,
sweep generator, demodulator, and raster scan logic. A
pair of terminal boards mounted adjacent to the tele-
scope pivot servo provides a junction for the Electronics
Assembly mating connector.

A circular aluminum shroud mounted on four standoffs
assists in the maintenance of acceptable operating
temperatures.

2.5.3.7   SUN SHADE AND SHUTTER

In order to permit tracking a guide star within 39
degrees of the sun line and 5 degrees of earth reflec-
tion, a carefully designed sun shade is extended beyond
the lens along the optical axis and affords sunlight
attenuation of the order of 1×10^{-11}. The assembly
consists of a machined aluminum tube about 2.5 inches
in diameter and 14 inches long containing black optical
baffles. A sun sensor and an earth sensor are mounted
adjacent to the open entry of the tube. A hinged
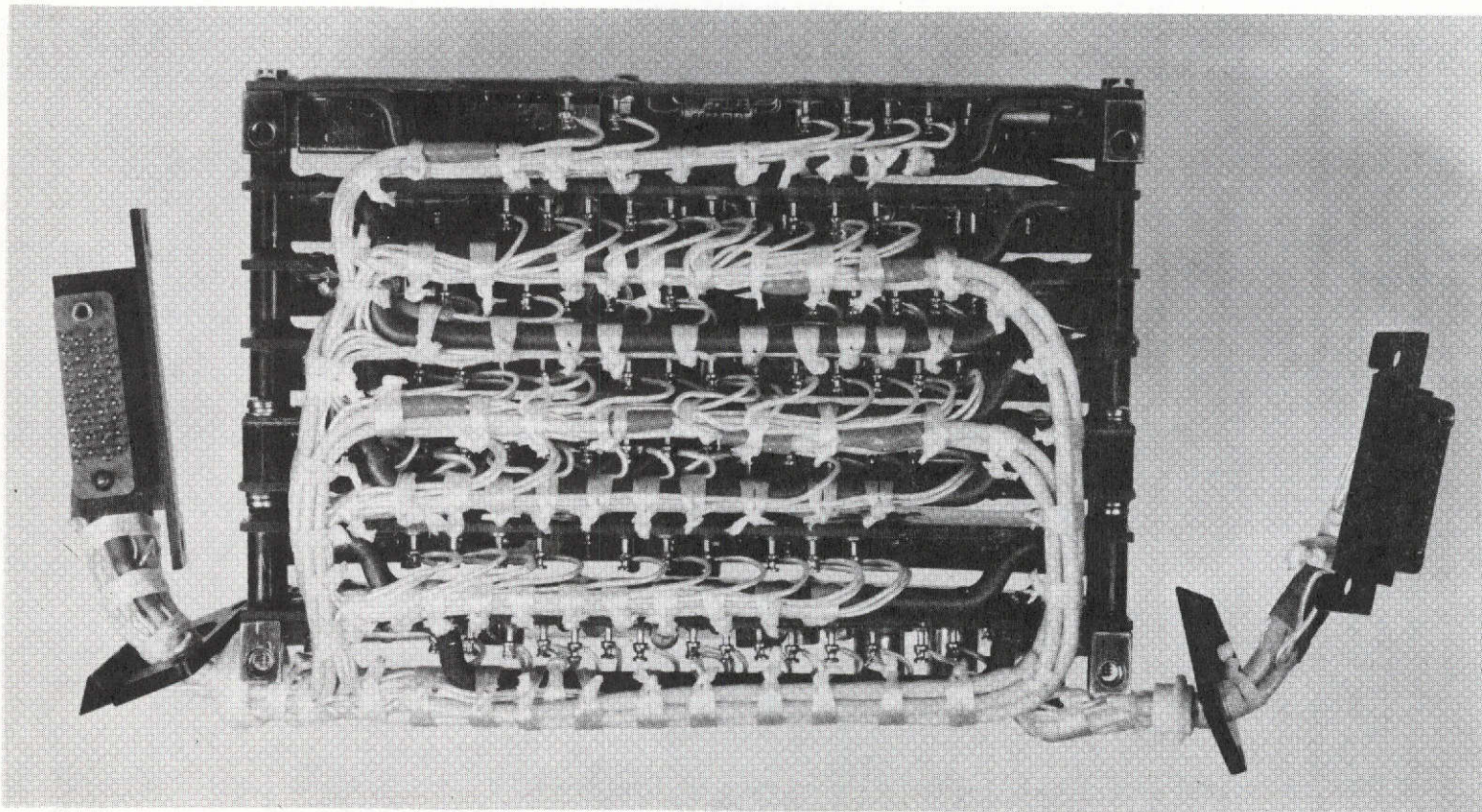
TELESCOPE ELECTRONICS ASSEMBLY
FIGURE 2.5.3.6-1

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Issue: Original
Date: May 22, 1969

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shutter-door provides closure of the tube against con-
tamination and damaging high-intensity stray light upon
manual or sensor command. The shutter is spring-loaded
to open, a steel tape wrapped around a drum returning
the door to closed position as required. Pull-force is
exerted on the tape by means of a jackscrew and nut
driven by a dc torque motor. A pair of hermetically
sealed snap-action switches control drive travel and
signal door position. Positive non-jamming mechanical
stops are provided at each end of the nut excursion.
A spring element in series with the tape maintains
tension on the link with the door in closed position.
Actuating time to fully close is about 600 milliseconds.

Dry-film lubrication is used on the jackscrew and
bearings throughout. Ball bearings are equipped with
TFE, glass, M_0S_2 composition separators. The motor is
thermally isolated from the shade and covered by a
shroud for protection against temperature extremes.
A stable encapsulating resin and tantalum-moly brushes
control outgassing and commutator wear to a low level.
The shade is thermally isolated from the telescope by
an epoxy-fiberglass spacer. Attachment is by five
capscrews and an electrical connector completes the
circuitry to the telescope electronics module.

2.5.3.8   GIMBAL TORQUER PIVOTS

Modular Torquer Pivots containing mostly common parts
are used to support one end each of the gimbal and
telescope respectively. The pivot consists of a housing,
shaft, bearings, torque motor, rate tachometer, flex
leads, terminal board and cover, Figure 2.5.3.8-1.
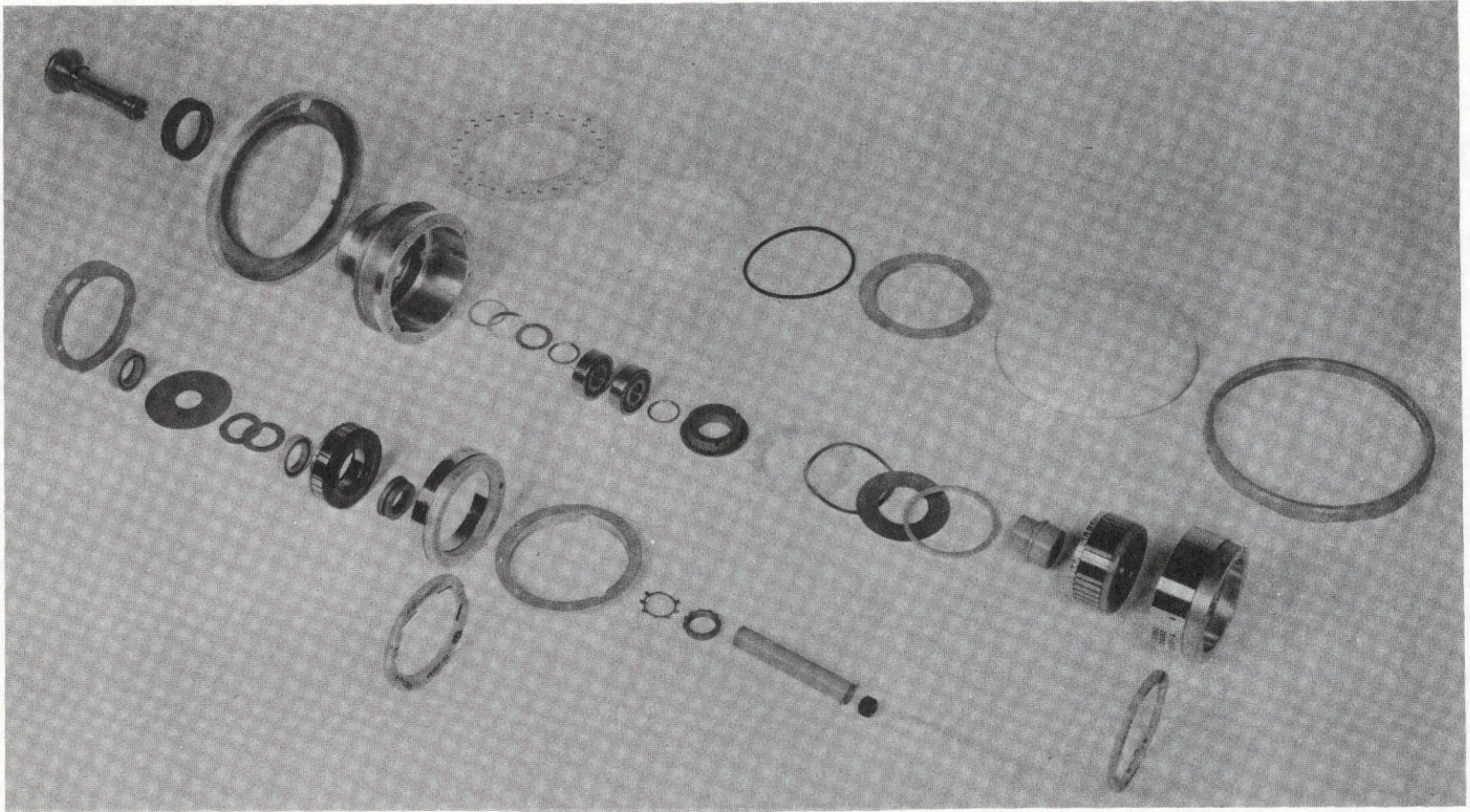
TORQUER PIVOT MODULE (INNER)
2125170-1
FIGURE 2.5.3.8-1

The housing is turned from aluminum alloy barstock and contains a corrosion resistant steel bearing liner and threaded inserts. A pair of 440 C preloaded angular contact ball bearings accurately pivots the shaft on which the motor and tachometer rotor adapters are mounted. An iron alloy shield disc minimizes magnetic field coupling between the motor and tachometer. To insure positive clamping force under worst cold temperature conditions, a BeCu wavy washer is included in series with the retaining nut and locking tab washer.

Within the hollow pivot shaft is contained a flex lead assembly for the purpose of conducting circuitry from gimbal to gimbal without the use of slip rings. The leads are TFE insulated silver alloy, gripped by a Viton grommet at the base of TFE bellmouth tube liner. Leads flex in torsion mainly and are clamped at the periphery of the fanout in a slotted teflon retainer disk, finally terminating at individual feed-throughs in the pivot terminal disk. Leads soldered to the backside of the feedthroughs terminate either in the electrical connectors (outer), Figure 2.5.3.8-1 or interconnect with the other torquer pivot, Figure 2.5.3.8-2.

Motors and tachometers are of permanent magnet pancake configuration employing a wound rotor encapsulated with approved resin. The tantalum-moly composition brushes used were selected for superior life when operating in a vacuum environment. Attachment of the torquer pivot shaft to gimbal is by means of a threaded ring and flange, torque being delivered through a captive pin
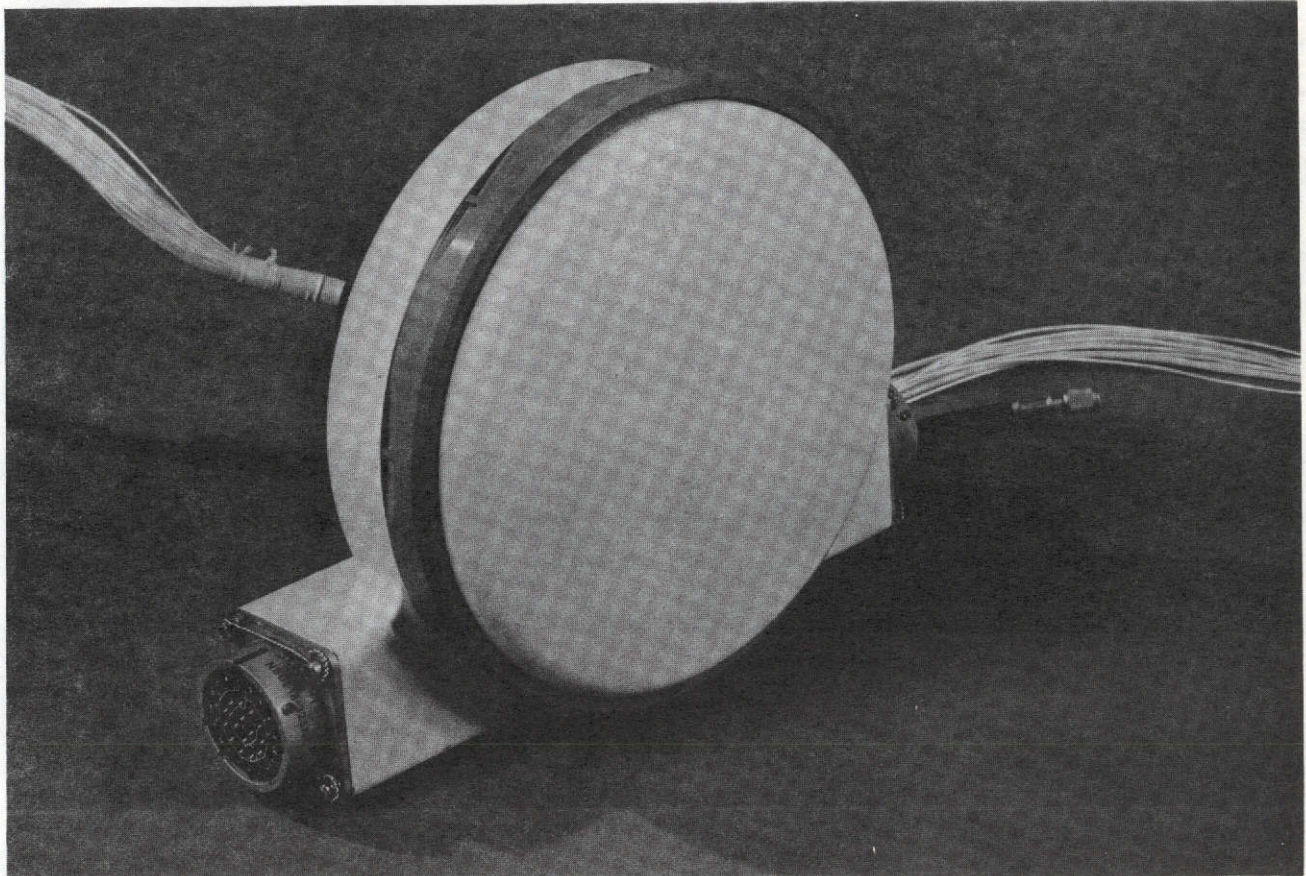
OUTER PIVOT TORQUER
2125180-1
FIGURE 2.5.3.8-1
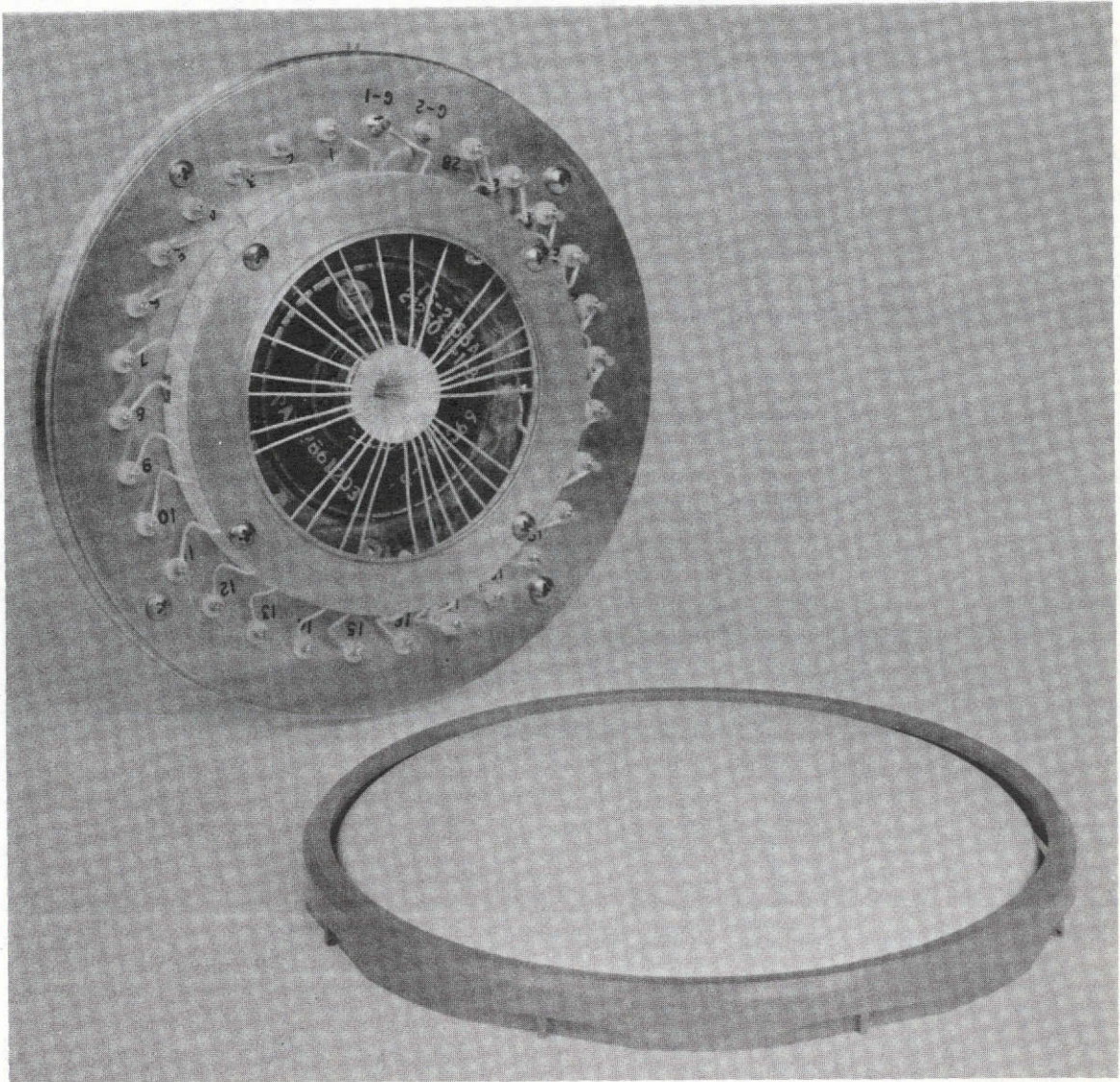
INNER TORQUER PIVOT
ATM ST - OMA   2125170-1
FIGURE 2.5.3.8-2

in the flange. The torquer housing body contains a
pilot diameter, locating pin, and a threaded ring means
of retention. To insure interchangeability, each assembly
is constructed such that a close tolerance dimension is
held between the locating flanges on the housing and
the shaft.

2.5.3.9 ENCODER PIVOT

The function of supporting the gimbal or telescope on
the encoder side is not shared by the encoder assembly
but rather by a separate pair of trunnion bearings.
This is done so as to relieve the optical disk hub from
forces generated during launch. The trunnion is comprised
of a flanged shaft, a pair of angular contact ball bear-
ings identical to those in the torquer pivot, a housing
liner, and associated threaded rings, nuts, and tab
washers. Rotational coupling between the pivot shaft
and the encoder disk hub is by means of a metal bellows.

The pivot shaft is hollow-bored for insertion of a
porous lubricant reservoir, vapors being conducted to
the region of the bearings via a drilled passage. A
threaded hole in the end of the shaft accepts an optical
alignment tool consisting of an adjustable mirror. The
mirror is adjusted in conjunction with an autocollimator
to define the actual gimbal axis.

2.5.3.10 ENCODER ASSEMBLY

The function of the Optical Encoders is to provide
gimbal angle information to the digital electronics in
the form of 16 bit serial gray code. The assembly, Figure
2.5.3.10-1 consists of a hub, mounting plate, angular
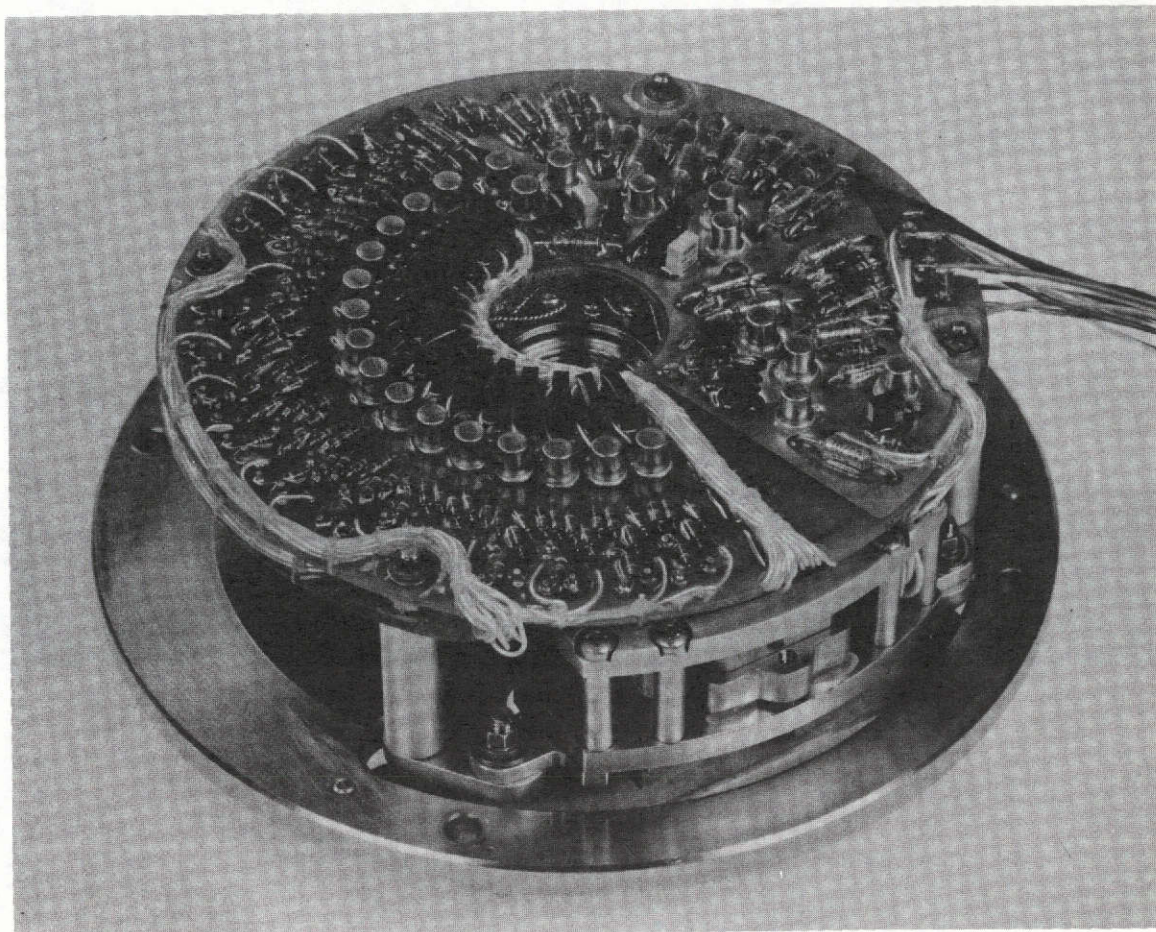
OPTICAL SHAFT ENCODER
FIGURE 2.5.3.10-1

contact bearing pair, coded optical disk, light source read-
out array, and a pair of printed circuit component boards.
The optical disk contains a code pattern consisting of
alternate transparent and opaque segments arranged in
concentric annular rings. The disk is precisely centered
on the highly accurate hub which has been ground after
assembly to control runout of the disk mounting face.
The light source consists of a high-rel tungsten filament
lamp, its beam focused by a truncated cylindrical lens.
The beam, 100 microinches wide is focused on the disk.
Photocells form a detector array on the opposite side
of the disk, the signals from which are amplified,
compared to a reference level, and digitized. The
resulting angle information is unique for each position
of the gimbal.

Structural parts of the assembly are constructed largely
of 309 stainless steel, with selected parts of 6 Al 4V
titanium and 400 series cres steel to compensate for
certain thermal gradients. The 440 C bearings are
preloaded in the DB configuration for maximum shaft
stability. Molecular seals minimize contamination of
bearings and lubricant escape. A pair of opposing
adjustment screws are used to position the encoder
mounting plate with respect to the structure during the
zero-adjust procedure, after which the plate-mounting
capscrews are tightened and the adjust screws secured.
Figure 2.5.3.10-2 shows an encoder hub mounted on a
work plate.

FIGURE 2.5.3.10-2

2-109
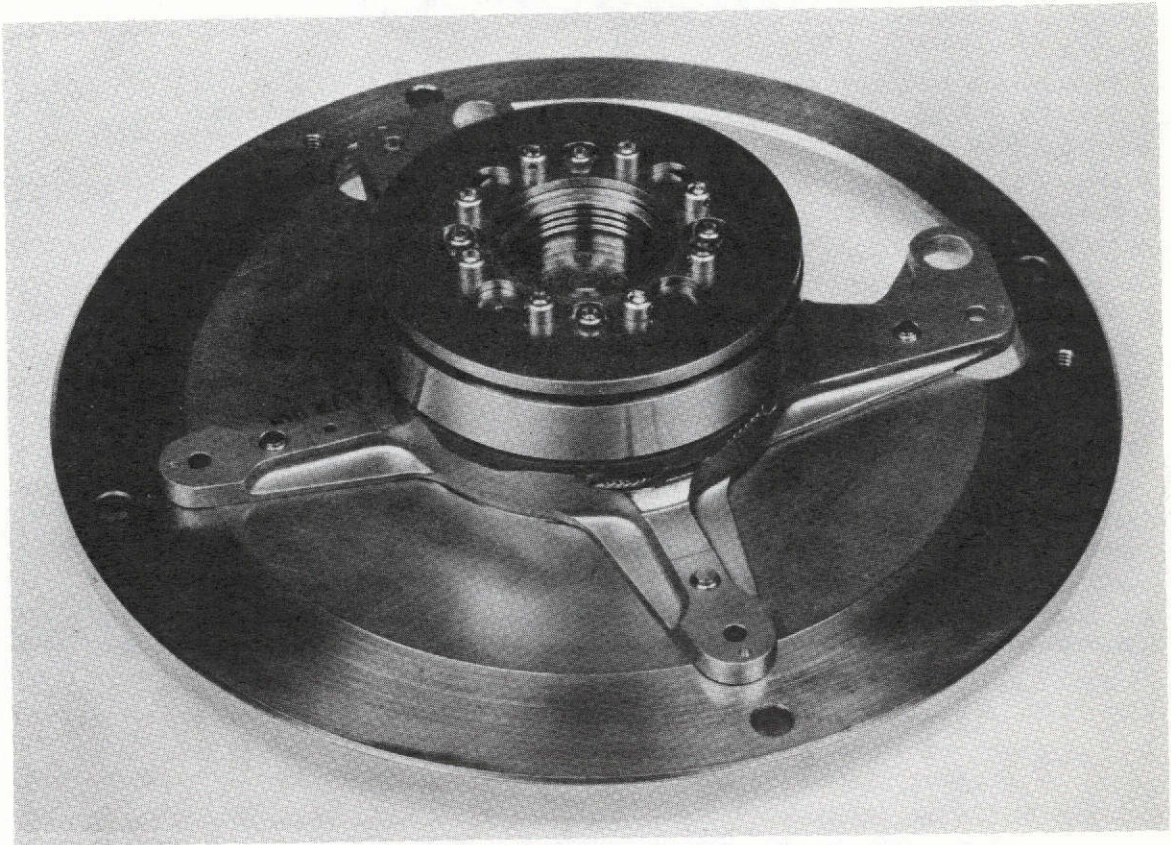
2.5.4   LUBRICATION

To provide long-term reliable lubrication with the
smooth performance required for a precision optical
device, a system employing a fluorosilicone oil is used.
The viscosity of this class of oils is least sensitive
to large temperature variations. Porous "Nylasint" ball
separators have a controlled void, 20 percent by volume,
which is vacuum impregnated with the oil. Additional
lube storage is contained in a similar supplementary
"reservoir" pad in proximity to the bearings. The
mechanism by which the oil reaches the ball zone is
one in which a vapor-pressure equilibrium is achieved
within the pivot cavity. Transport is molecular in
nature and varies with temperature. Undesirable
flooding is avoided as is the somewhat higher attendant
torques associated with the use of channeling grease.

Escape of lubricant from the confined cavity is effectively
controlled by three means. First, a teflon face-seal
element is provided on each of the four rotating pivot
shafts. A tempered BeCu spring maintains seal contact
with a mating stainless steel washer. In addition to
this rubbing contact seal, molecular seals sometimes
termed labyrinth seals flank both sides of each bearing
cavity being designed for minimum radial clearances
and maximum axial length. Tests conducted have verified
the approach and agree well with theoretical calculations
of vapor loss. Thirdly, migration of lube over the
surfaces of parts in the escape path is minimized by
application of a dry oleophobic coating with a selected
"surface energy" level.

2.5.5 THERMAL CONTROL

2.5.5.1 REQUIREMENTS

Certain components within the OMA may be damaged or permanently degraded if subjected to temperature extremes beyond design limitations. Furthermore, in order to meet performance specifications, even tighter temperature control must be exerted. These means are employed to influence tracker temperature: insulation, application of heater power, and passive methods involving surface finishes.

2.5.5.2 INSULATION

Where low thermal conductivity must be maintained across an interface requiring structural integrity a wafer or spacer of a rigid plastic or other selected material is used. For example, to prevent escape of thermal energy from the telescope housing to the sunshade, a spacer of rigid filled epoxy-fiberglass is clamped between the shade flange and its mounting pad on the housing and again between the shutter drive motor and its mounting pad on the shade.

On the other hand, decidedly more efficient insulating effect is realized from the use of multi-layer aluminized Mylar as is used between the Encoder Cover sandwich shells and in the frame belly pan cover where structural support is not of primary concern.

2.5.5.3 ELECTRIC HEATERS

Resistance heaters and thermal snap-switches are mounted
in the telescope and the gimbal and frame encoder chambers
totalling 20 watts. These elements are switched in and
out by a redundant array of four disc-type hermetically
sealed snap switches.

2.5.5.4 THERMAL CONTROL FINISHES

By choosing a finish with a preferred ratio of solar
absorptivity to thermal emmissivity, a surface may be
made to accept or reject BTU. Selected finishes have,
therefore, been applied per this principle. In general,
inside surfaces, or those not in the sun view, are painted
with Cat-a-lac epoxy black paint. Surfaces external
are painted with Pyromark white, a silicone resin based
paint.

2.5.6 WIRING

A pair of PV type 32 pin bayonet-latch connectors are
located on the outer torquer pivot housing accommodating
all OMA power and signal circuits. Each torquer pivot
is wired as a subassembly module ready for installation.
Hookup is accomplished by trimming the leads to proper
length and soldering to pertinent terminals in the next
assembly. Wire bundles are securely laced to tie bars
provided. Encoders likewise are prewired and tested at
the subassembly level as is the telescope. As mentioned
earlier, the Telescope Electronics Assembly provides
two rectangular miniature connectors at the telescope
interface junction.

Wire used throughout is silver alloy with transparent
teflon insulation.   In particular, flex leads are 30 AWG
with 19 x 42 stranding.

2.5.7   ALIGNMENT REFERENCE

To assist in location of the optical axis and for check-
out of alignment with respect to vehicle, a reflective
reference is attached to the OMA frame on the torquer
pivot end.   The device may be viewed from the zenith
direction and a position normal to the same.   A pair
of cross-hair scribe lines are used to locate the optical
axis zenith, dimensions from the axis to each reference
line being recorded in the data package accompanying
each tracker.   A smaller reflective element attached to
the cylindrical sun shade is provided for test procedure
purposes.

SECTION 3

3.0   SYSTEM TEST EQUIPMENT

Two identical dark rooms are equipped with seismic
blocks and Diffraction Ltd. star simulators. The star
simulators can be accurately moved through 120 degree
arc corresponding to IG rotation. The optical-mechanical
assembly (OMA) is also mounted on an optical-mechanical
table and can be rotated through a 180 degree arc.
This corresponds to OG rotation. The tables are posi-
tion accurate to 5 arc seconds and they are aligned
perpendicular to eac other to within 3 arc seconds with
the aid of two autocollimators and an optical master.
The combined effect of the two tables is to accurately
locate the simulated star anywhere within the range of
gimbal movement of the star tracker. The electrical
test console simulates the spacecraft signals and loads.
Extensive monitoring and readout devices are available.
In addition, a minimum of eight channels of Sanborn
strip chart oscillograph recording provides a permanent
record of the star tracker performance.

Figure 3-1 shows the earth albedo simulation utilizing
a Spectra Prichard photometer.

3.1   Alignment of Final Functional Test Stand

Qualification and Acceptance Function Testing of the
ATM system are performed on the Final Functional Test
stand, shown in Figure 3-2.

The star tracker OMA is mounted on the mounting bracket
and plate on the optical rotary table with the outer
gimbal axis parallel to and coincident with the axis
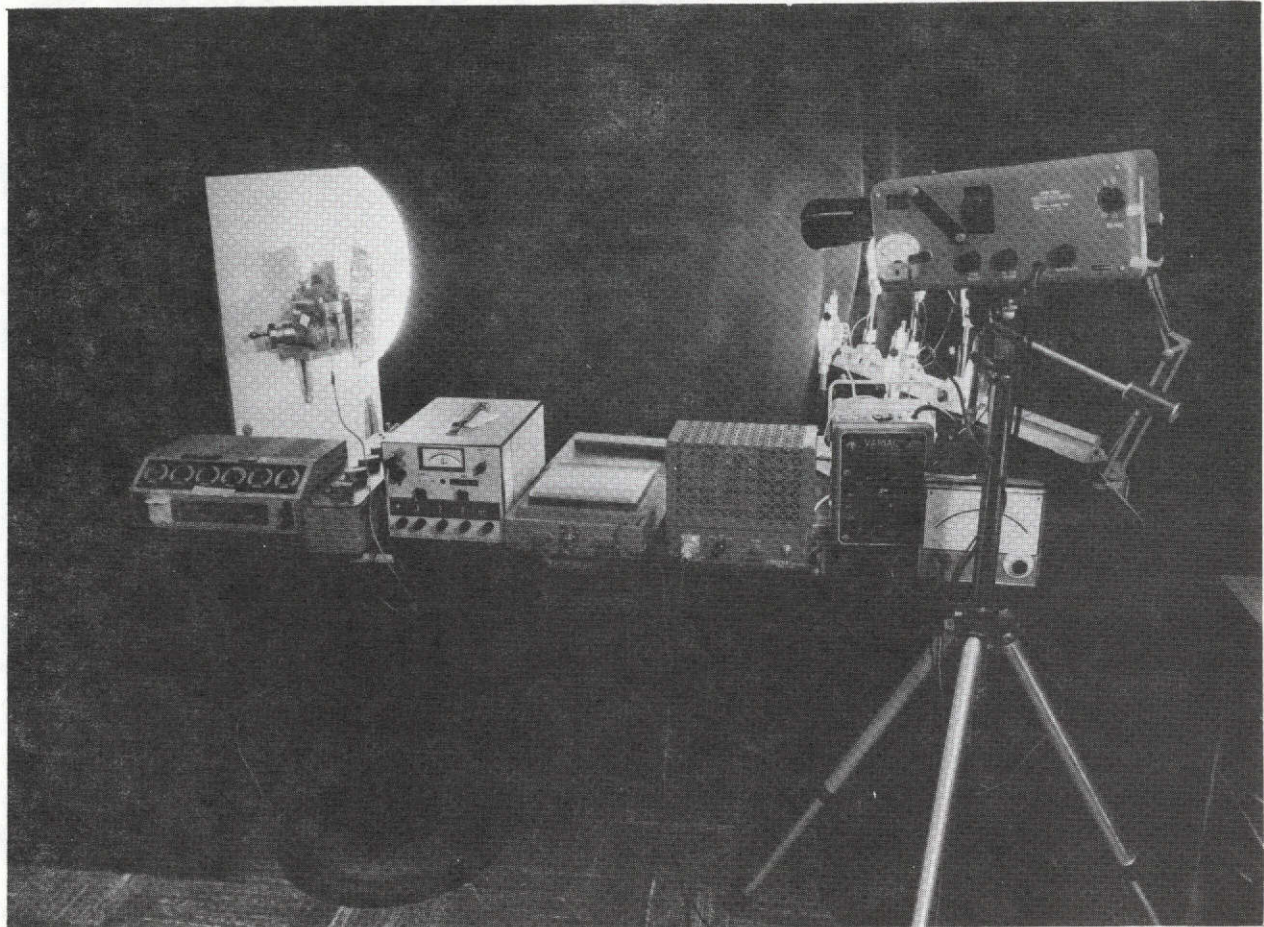
EARTH ALBEDO SIMULATOR
FIGURE 3-1
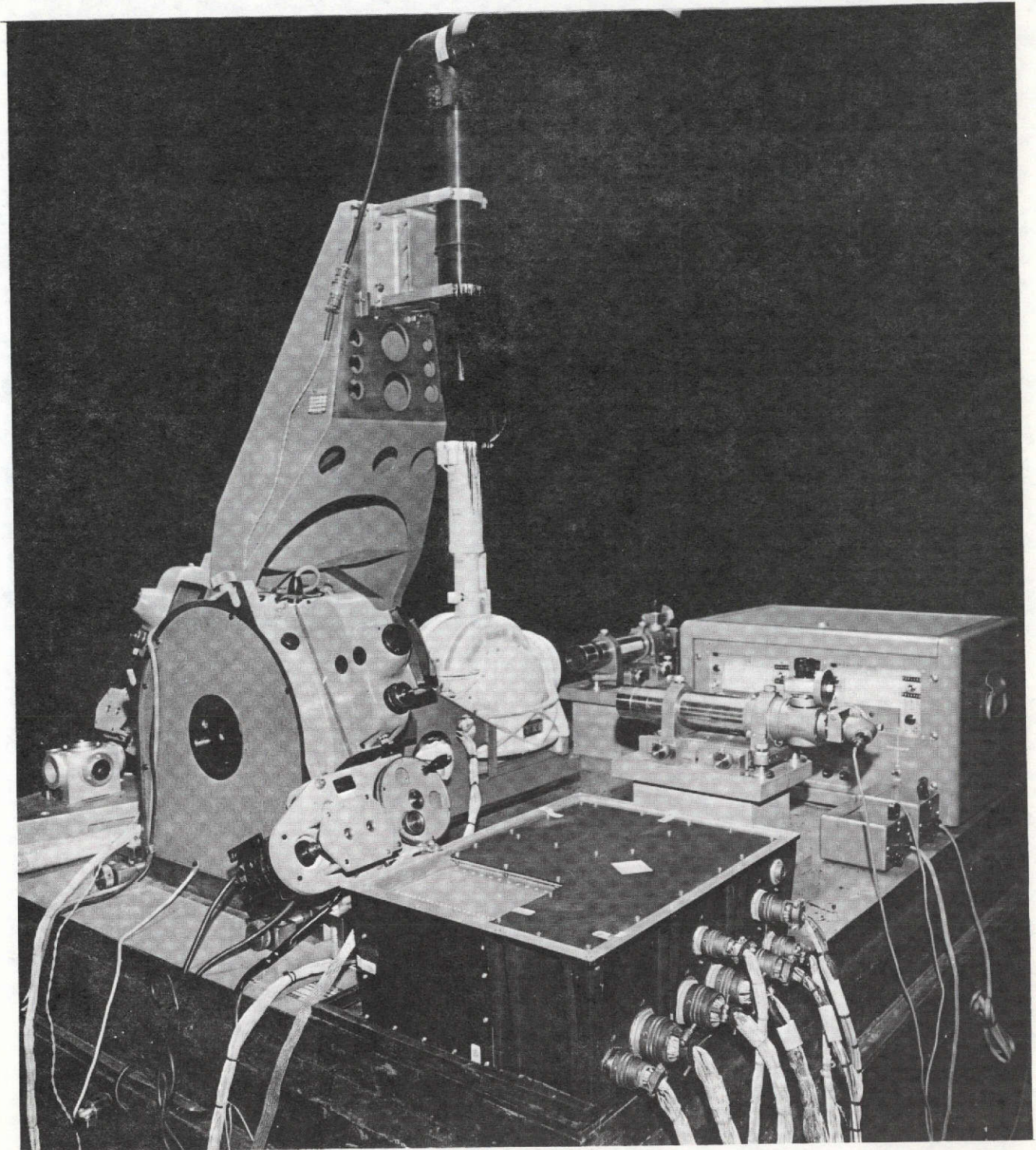
ATM FINAL ALIGNMENT ROTATING TEST SET UP
FIGURE 3-2

72-262-5

of rotation of the rotary table. The axis of rotation
of the star simulator rotary table is oriented ortho-
gonal to and approximately intersecting the axis of
rotation of the OMA rotary table. The collimated beam
of the simulated star, at the zero setting of its
rotary table, is orthogonal to both axes of rotation
and approximately intersects their point of intersection.
Both rotary tables are capable of manual movement and
may be positioned to any fixed angle within the required
range of travel. They are both capable of arc second
readout accuracy. The drive system is capable of pro-
viding rates from 0 to 1.5^{o}/sec.

Of particular interest is the thermal-vacuum chamber
expecially built for testing star trackers, Figure
3-3.

It has a working area 5 ft. long x 3 ft. diameter, which
is divided into two sections by a bulkhead. Dual en-
vironmental controls allow simultaneous testing with
two different temperature profiles. The chamber is
constructed with optical quality windows used for ex-
ternal star references and for monitoring the platen
position. It may be operated at temperatures from
-300°F to $+350^{o}$F and pressures from sea level down to
1×10^{-9}mm Hg.

3.2   Star Tracker Alignment and Test Equipment

The Star Tracker Optical Mechanical Assembly is sub-
jected to optical alignment and inspection at numerous
stages of its manufacture, including a final assembly
inspection. The optical axis is aligned perpendicular
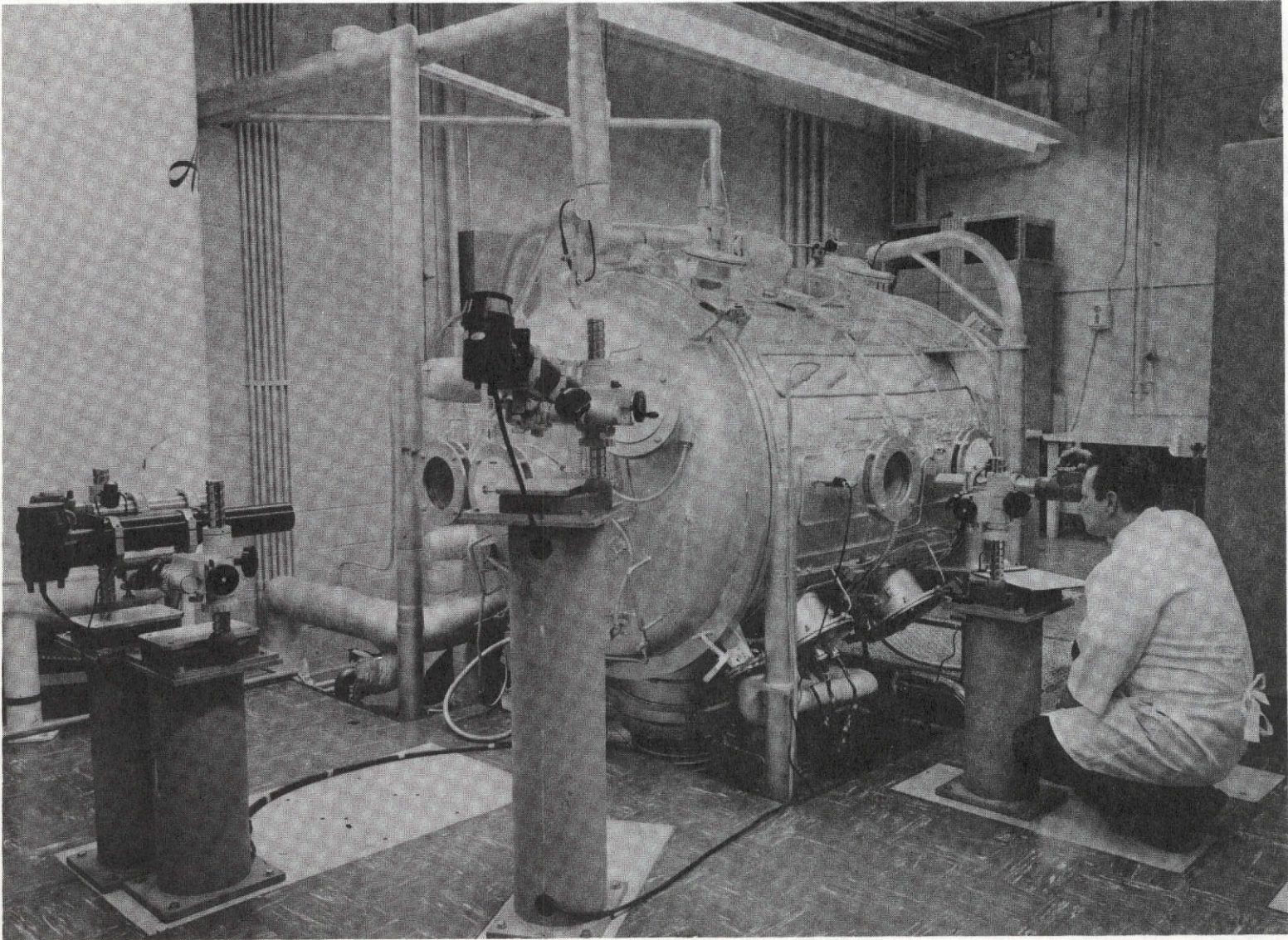
THERMAL VACUUM TEST FACILITY
FIGURE 3-3

to the plane of the rotational axes with a 3 sigma
accuracy of 15 arc-seconds. Inner and outer gimbal
axis orthogonality is limited to 10 arc-seconds, 3
sigma. The three-point mounting configuration (two
two-axis pad) is machined and lapped until the planes
described by the pads are parallel to the outer gimbal
axis to within 15 arc-seconds, 3 sigma.

3.3   Final Check Out Console (130F751)

3.3.1   Uses of the F.C.O.

The electrical Final Checkout Console 130F751 is used
to perform final exceptance testing and qualification
testing of Star Tracker System for the Apollo Telescope
Mount (ATM). The Star Tracker consists of an Optical
Mechanical Assembly (OMA) 2125000-1 and a Star Tracker
Electronic Box (STE) 2125600-1.

The FCO supplies and measures all necessary excitations
and signals to the star tracker including 0-6 VDC supply
for simulated star.

The FCO has readout capability for all star tracker
performance tests.

3.3.2   Test Configurations

3.3.2.1   Ambient Condition Testing

The 130F751 FCO is used with the 130E226 Mechanical
Test Station and the Star Tracker dark room (Bendix
Facility) to perform ambient testing.

3.3.2.2   Thermal Vacuum Testing

Use 130F751, Thermal Vacuum Cables No. 1938554 and
Thermal Vacuum Chamber (Bendix Facility) to perform
thermal vacuum testing.

3.3.2.3   Hot/Cold Testing at Ambient Pressure

Use 130F751 FCO with cables and Hot/Cold Chamber
(Bendix Facility) cable No. 1938555.

3.3.2.4   Solar Impingement Test

Use 130F751 FCO with Solar Impingement cables No.
1938556 and Solar Impingement Mounting Fixture
Testing is done at GE, Valley Forge Facility.

3.3.2.5   Electromagnetic Compatibility Testing

Use 130F751 FCO with EMC cables No. 1938557. Test is
performed in shielded rooms. (Loki Building - Bendix
Facility).

3.3.2.6   Acoustic Noise Testing

Use 130F751 FCO with No. 1938558 cables.

3.3.3   Test Stand Description - See Figures 3.3.3-1 and
3.3.3-2.

3.3.3.1   Power Breaker Panel 1938472 contains two 15A breakers
and controls 115V 60 Hz power to two independent plug
molds inside console.
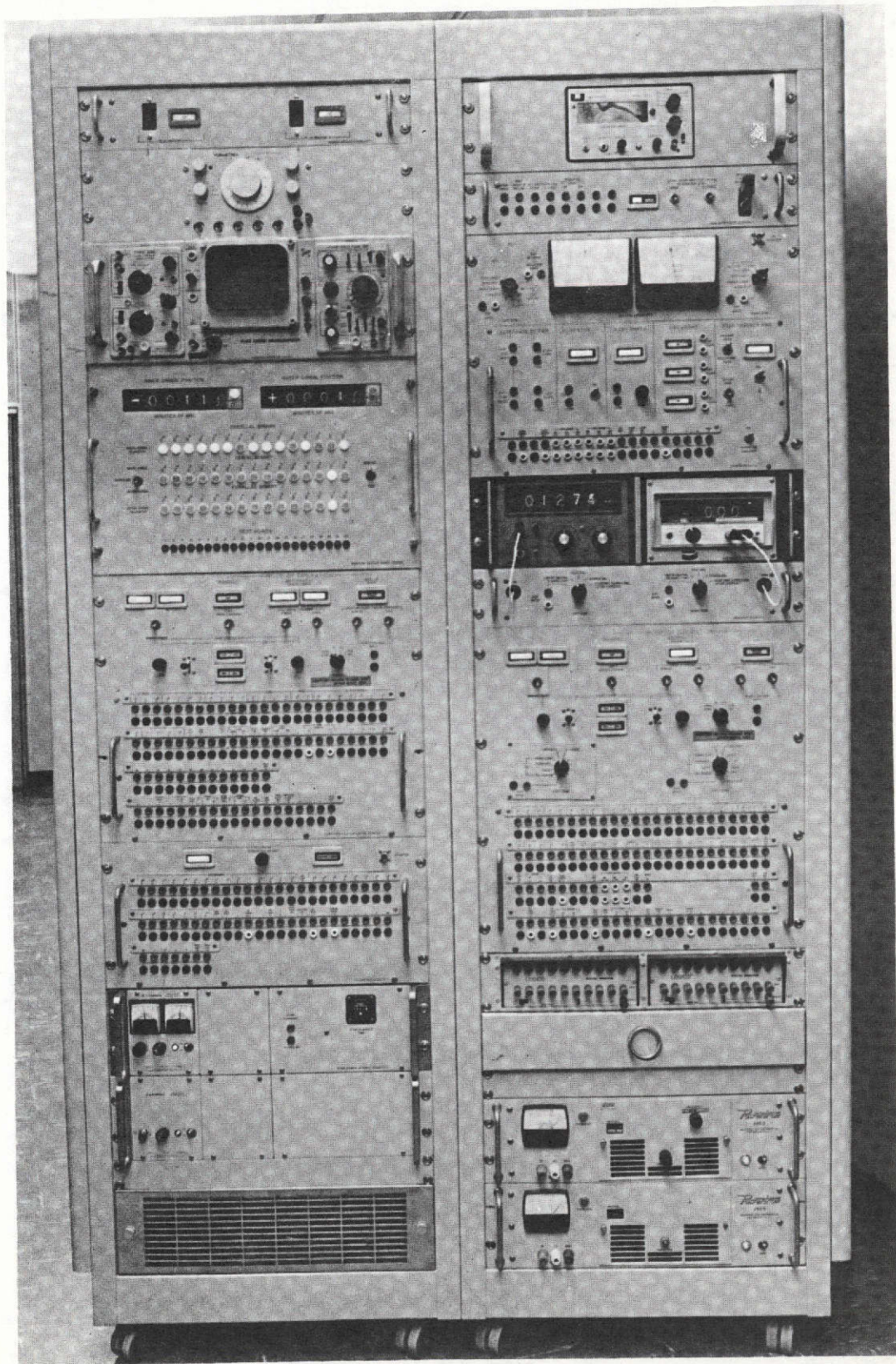
ATM STAR TRACKER FINAL TEST STAND CONSOLE
FIGURE 3.3.3-1

← — 19.00 REF — →
(TYP)

3.1 — PWR BREAKER PNL 1938472-1	BLANK PANEL 1751038-2
3.2 — FUNCTION GENERATOR WAVETEK MODEL 100A	COUNTER MONSANTO MODEL 100A — 3.9
3.3 — OSCILLOSCOPE TEKTRONIX MODEL 561 Plug-In 3A6 Time-Base 3B3	POWER PANEL 1938459-1 — 3.10
3.4 — POSITION DISPLAY PANEL 1938268-1	VOLTMETER PNL 1938423-1 (Left DVM) (Right DVM) — 3.11
3.5 — COMPUTER C AND D SIMULATOR PANEL 1938269-1	READOUT PANEL 1938271-1 — 3.12
3.6 — TELEMETRY PANEL 1938272-1	TEST PANEL 1938273-1 — 3.13
3.7 — STAR SIMULATOR POWER SUPPLY PNL 1938270-1	DIGITAL MONITOR INDUSTRIAL INVENTIONS BPL-10 BL-10 — 3.14
3.8 — +28V UNREG POWER SUPPLY LAMBDA 8554	PREMIER DRAWER D-2316
BLANK PANEL 1751038-1	BLANK PANEL 1751038-1
FAN KOOLTRONICS KP 525	0-160V 400Hz 3ϕ POWER SUPPLY POWERTRON 4466 (FFO Pϕ) — 3.15 (XA)

FIGURE 3.3.3-2

3-9

3.3.3.2   Function Generator; Wavetek Model 100A can be patched
          into "Function Generator Input" on the Computer, C and
          D Panel 1738269 or into the "Function Generator Input"
          on the Test Panel 1938273 to perform servo loop fre-
          quency response tests.

3.3.3.3   Oscilloscope - Tektronix Model 561 mainframe with a
          3A6 (Dual Channel, 10 MHz) plug-in and a 3B3 (Delay
          Sweep-Time Base) plug-in.   For all test points using
          red (hi) and black (lo), use a properly adjusted
          Tektronix 10:1 probe on red (hi) jack only.   For sig-
          nals not referenced to ground (lower jack not black),
          use scope in its differential mode, (use two 10:1
          probes and place 3A6 mode switch to "Added".)

3.3.3.4   Position Display Panel 1938261

3.3.3.4.1 Outputs from Display Panel to STE

          The Position Display Panel provides Inner and Outer
          gimbal Interrogate Commands (to J4-K, J4-L) and ATM
          DC Clock Pulses (to J4-M).   The above signals are de-
          rived from a crystal oscillator and are used to shift
          out serial binary information from the STE IG and OG
          Binary Storage Registers.

3.3.3.4.2 Inputs to Display Panel from STE

          Inner Gimbal position (J5-A through J5-R) is displayed
          on individual Bit Lights marked "Inner Gimbal Telemetry-
          Parallel Binary."

Outer Gimbal position (J5-T through J5-K) is display-
ed on individual Bit Lights marked "Outer Gimbal
Telemetry - Parallel Binary."

Serial Binary Position Signal

Inner Gimbal Serial Binary Signals (J4-G) are shifted
into a register and displayed on Bit Lights when the
toggle switch marked "Computer" is switched to "Inner
Gimbal."

Outer Gimbal Serial Binary Signals (j4-H) are shifted
into a register and are displayed on Bit Lights when
the toggle switched marked "Computer" is switched to
"Outer Gimbal."

Parallel Binary Coded Decimal Output from STE

The IG parallel BCD signals (J6-S through J6-F) and
the OG parallel BCD signals (J6-A through J6-R) are
decoded and displayed with nixie tubes.

Logic is used in the Position Display Panel to dis-
play the position to an accuracy of 0.5 minutes of
arc. For example; +3999.5 minutes of arc. Test
points numbered 1-22 monitor points internal to the
Display Panel and are not normally used.

3.3.3.5   Computer - C and D Panel 1938269

All pins from the STE connectors J4 ATM/DC and J6 ATM
Distributor are brought to test jacks along the lower
half of the panel. A series protective resistor

(Type 2.2K) is used to prevent damage to the Star
Tracker should any of the test points be accidentally
shorted.

Status is displayed by lighted indicators.

Commands are initiated with toggle switches. Hand
controller signals are simulated in the following
manner: Set Readout Panel to "Comp- C and D Hand
Contro." Use Hand Controller adj Knob to preset any
input between 0 to 5 volts as read on the digital
voltmeter. Move the Hand Controller switch upward
(spring return), the preset voltage will now be
applied to the Hand Controller Input (e.g., J6-t to
J6-u). A lighted indicator simultaneously appears
showing polarity of input. The opposite polarity is
obtained by moving level downward (spring return).

In the neutral position, zero volts is applied to
the Hand Controller Inputs.

3.3.3.6   Telemetry Panel 1938272

All pins on the STE connector J5 are brought to front
panel jacks with protective series resistors.

The Telemetry Panel generates a 278 microsec strobe
pulse four times a second to interrogate the STE
Telemetry Storage Registers.

Connect the Monsanto Counter to the BNC input labeled
"Counter" and rotate "Telemetry Strobe Pulse Adj"
until 278 microsecond pulses are obtained.

3.3.3.7   Star Power Supply 1938270

The Star Power Supply feeds a Diffraction Limited simulated
star source. Rotate Readout Panel (1938271) selector switch
to "Star Current" setting. Increase the current until the
proper star magnitude is reached as per attached calibration
chart - Lamp Current vs. Star Magnitude.

3.3.3.8   Unregulated +28V Power Supply

Provides +28V unregulated power. No adjustments are made
on this panel. The power supply is to be normally on;
unregulated 28V power to the Star Tracker is controlled on
the "Power Panel".

3.3.3.9   Counter

Monsanto Model 100A is used to adjust the telemetry sample
pulse, perform the AC power frequency variation test as
well as a general purpose counter/timer.

3.3.3.10   Power Panel 1938459

The Power Panel monitors and controls AC and DC excitation
to the Star Tracker.

Description of indicators and controls:

1.   The two wattmeters marked M1 and M2 measure the Star
     Tracker power consumption from the 115V 400Hz 3φ lines.
     The Two Wattmeter Method is used and the total wattage
     is the sum of the two readings.

2. The BNC output marked "J5 Counter" provides a 10V 400Hz signal suitable for triggering the counter. A step down transformer from the 115V line is used.

3. Two rotary switches marked Left and Right DVM allow monitoring of AC and DC voltages and currents on the two DVM's.

4. Box on panel marked "Alternate Power" - If $\pm$28VDC excitation instead of 115V 3ϕ power is desired, two external power supplies (28V at 2 amp minimum) can be connected to the four jacks enabled "Ext P/S No. 1" and "Ext P/S No. 2" with polarities as shown. Place right hand toggle switch to "Alt DC Power." Current shunts are provided. 0.1V corresponds to 1A.

5. Box on panel marked "Heater" - when toggle switch is thrown ON +28VDC power is supplied to the Star Tracker Heaters, the "Heater On" indicator will light. A current shunt is provided, 0.1V corresponds to 1A.

6. Box marked "+28V Unreg."

   "+28V unreg" indicator is lighted when the +28V P/S is energized. Monitor "+28V P/S" on left DVM. Use "Adj" knob to set +28VDC. A current shut is provided 0.1V corresponds to 1A.

7. Box Marked "115V 400Hz"

   Indicators ϕ_A, ϕ_B, and ϕ_C will light if 3ϕ power supplies are on and "400Hz 3ϕ Breaker" is ON. Three

current transformers with precision loads labeled "ϕ_A curr, ϕ_B curr, and ϕ_C curr" provide a voltage isolated from the 115V 3ϕ such that 1 VAC corresponds to 0.1 amperes.

8. Box marked "Star Tracker Power"

Place toggle switch to Primary Path." This applies unreg. +28VDC via pins J3-B to J3-A. 115V 3ϕ is applied via J3-E, J3-F, J3-G.

In the "Redundant Path" position unreg. +28VDC is applied via pins J3-D to J3-C. 115V 3ϕ is applied via J5-H, J3-J, J3-K.

The toggle switch marked "Alt. DC Power"/"AC Power" applies external +28V power supplies to J3-M, J3-L, J3-N and disconnects 115V 3ϕ excitation in the "Alt DC Power" position. 3ϕ power is applied and the external supplies are disconnected in the "AC Power" position. When the toggle switch labeled "Star Track Pwr" is switched to ON the Star Tracker system will be energized. (115V 3ϕ and 28V unreg. is applied simultaneously.) The indicator "Star Track Pwr On" will light.

9. All pins from STE connector J3-ATM power distributor are brought to front panel jacks through protective series resistors (Typ. 2.2K)

3.3.3.11   Voltmeter Panel 1938423

The voltmeter panel mounts two digital voltmeters to allow simultaneous monitoring of both gimbals. The left DVM is a Fairchild Mod 7000 (4 digit 0.02% Acc on DC, with autorange and AC plug-in option. The right DVM is a Systron Donner Mod 9000 (3 digit 0.2% Acc on DC and OHMS scales.)

3.3.3.1.2   Readout Panel 1938271

The readout panel channels signals from the various panels to the digital voltmeters. Two level switching is used. For example, to monitor the IG tach output on the Test Panel, the "Left DVM" selector switch on the readout panel must be in the "Test Panel" position and the "Left DVM" selector switch on the Test Panel must be placed into the "IG Tach" position.

3.3.3.13   Test Panel 1938273

All pins from the STE connectors J7 and J8 are brought to test jacks through series protective resistors (Typ. 2.2K) Star Tracker status is displayed on lighted indicators. Analog voltages from the Star Tracker can be channeled to the left and right digital voltmeters.

The hand controller, set-up is identical to the Computer – C and D Panel.

3.3.3.14   Logic Monitor Panel

The Logic Monitor Panel provides twenty independent lamp
drivers and lamps. The lamps light when an input signal is
more than 0.9 volts above reference. The input impedance
is 1 megohm and inputs up to +40 volts are permissible.

3.3.3.15   AC Power Supply

Two 250 watt AC power supplies, connected in an open delta
configuration, provide 115V 400Hz 3ϕ excitation to the
Star Tracker. The output voltage is variable from 0 to
160 volts and the frequency is variable from 390 to 410 Hz.

Power supplies are to be normally on; AC power to the
tracker is controlled on the "Power Panel".

SECTION 4

4.0   QUALIFICATION PROGRAM

The serial number 0003 ATM Star Tracker System, which
contains an Optical Mechanical Assembly Bendix Naviga-
tion and Control Division Type Number 2125000-3 (NASA
50M22145) and a Star Tracker Electronics package BNCD
Type Number 2125800-1, (NASA 50M22146) was successfully
qualification tested to BNCD GQTP document 2124424.
The qualification tests were performed over the time
interval from July, 1971 to January, 1972.

A list of the qualification tests the ATM Star Tracker
was subjected to along with the applicable test pro-
cedure section numbers, are listed in Table 4.1 titled
"Qualification Tests Performed". A summary of the
functional test data recorded prior to, during, and
after the total qualification test is listed in Table
4.2 titled, "Summary of the Results of the Functional
Tests Performed During Qualification Testing". The
intent of the qualification test was to subject the
ATM Star Tracker, which was built to production draw-
ing and representative of the product configuration
baseline, to tests which would demonstrate that the
unit conformed to the contractual design requirements.

TABLE 4.1

QUALIFICATION TESTS PERFORMED

Star Tracker Package consisting of:

Optical Mechanical Assembly BNC Type No. 2125000-3

Star Tracker Electronics BNC Type No. 2125800-1

Test Procedure: BNC Document No. 2124424 (GQTP)

TEST	TEST PROCEDURE PARAGRAPH
Examination of Product	4.2.1
Full Functional (Initial)	4.2.2
Electromagnetic Interference	4.2.10
Thermal Shock	4.2.7
High and Low Temperature	4.2.4
Full Functional (Post High and Low Temp.)	4.2.2
Vibration	4.2.9
Acceleration	4.2.8
Acoustical Noise	4.2.6
Thermal Vacuum	4.2.5
Circuit Transients	4.2.11
Full Functional (Final)	4.2.2
Outgassing	4.2.3

TABLE 4-3
SUMMARY OF THE RESULTS OF THE
FUNCTIONAL TESTS PERFORMED
**DURING QUALIFICATION TESTING**

4-3

The results of the various tests are as follows:

1) The optical mechanical assembly and the star
    tracker electronics package were mechanically and
    electrically inspected per 2124424 (GQTP) 4.2.1
    and were found satisfactory.

2) The star tracker was next subjected to the initial
    full functional test per 2124424 (GQTP) 4.2.2. Ex-
    cept for the star threshold level, the results of
    the test were within specified limits and the
    tracker operation was satisfactory. The minimum
    allowable star threshold sensitivity has a magni-
    tude of +1.09. The measured tracker star threshold
    sensitivity was +1.08. The star standard calibra-
    tion was then checked, found to be slightly out of
    calibration, and the source of the out of specifica-
    tion condition determined to be due to this condi-
    tion. The actual star threshold value was then
    determined to be +1.09 magnitudes. It was concluded
    that the star tracker had successfully met its per-
    formance specification. Figure 4-1 illustrates the
    full functional testing configuration.

3) The star tracker was subjected to the electromagnetic
    interference test per GQTP 2124424 paragraph 4.2.10.

    The unit passed the susceptibility portion of the
    test but had some minor non-conformances to the
    conducted and radiated portions of the EMI require-
    ments. MSFC approved these deviations.
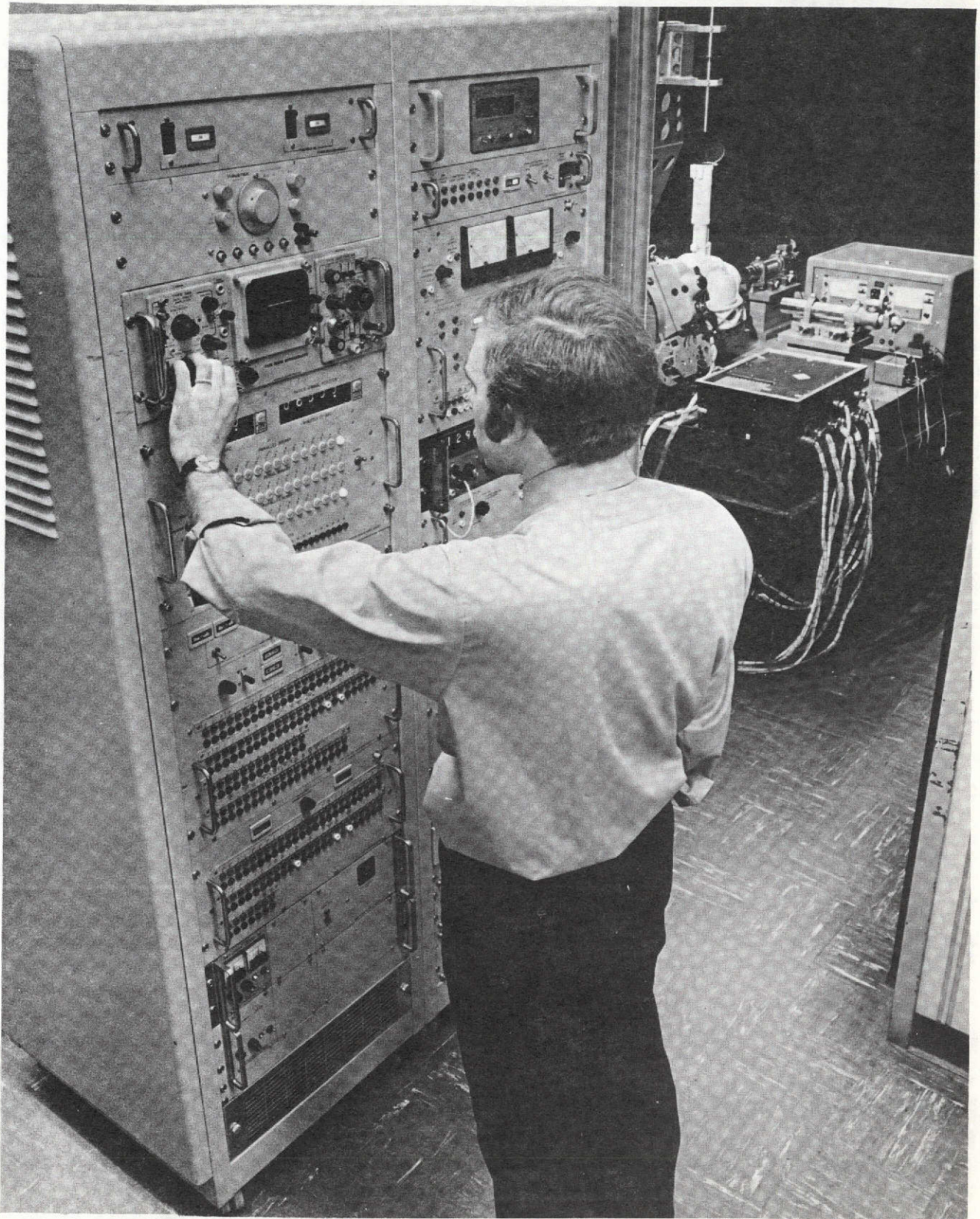
ATM STAR TRACKER FINAL FUNCTIONAL TEST
FIGURE 4-1

Following the EMI test, a functional test was performed on the system. There was no evidence of damage or deterioration to the system due to the EMI testing, with the results of the post EMI functional test within the specified limits.

4) The star tracker was subjected to the thermal shock per 2124424 (GQTP) 4.2.7. Following the exposure, inspection revealed no evidence of damage, operation was satisfactory, and function test results were within specified limits.

5) The star tracker was subjected to the high and low temperature test per 2124424 (GQTP) 4.2.4. Operation was satisfactory throughout, results were within specified limits, and there was no evidence of damage or deterioration as a result of the test.

   Following the high and low temperature exposures the units were functionally tested with the results within specified limits.

   Figures 4-2 through 4-4 illustrate the thermal facuum test configuration for the OMA and STE.

6) In late September 1971, the Qualification Star Tracker serial number 0003 was modified, incorporating additional restraint to the phototube assembly and improving the shutter drive mechanism. These modifications were incorporated into the flight hardware at the same time. The modifications were coordinated with, and approved by NASA/MSFC personnel.
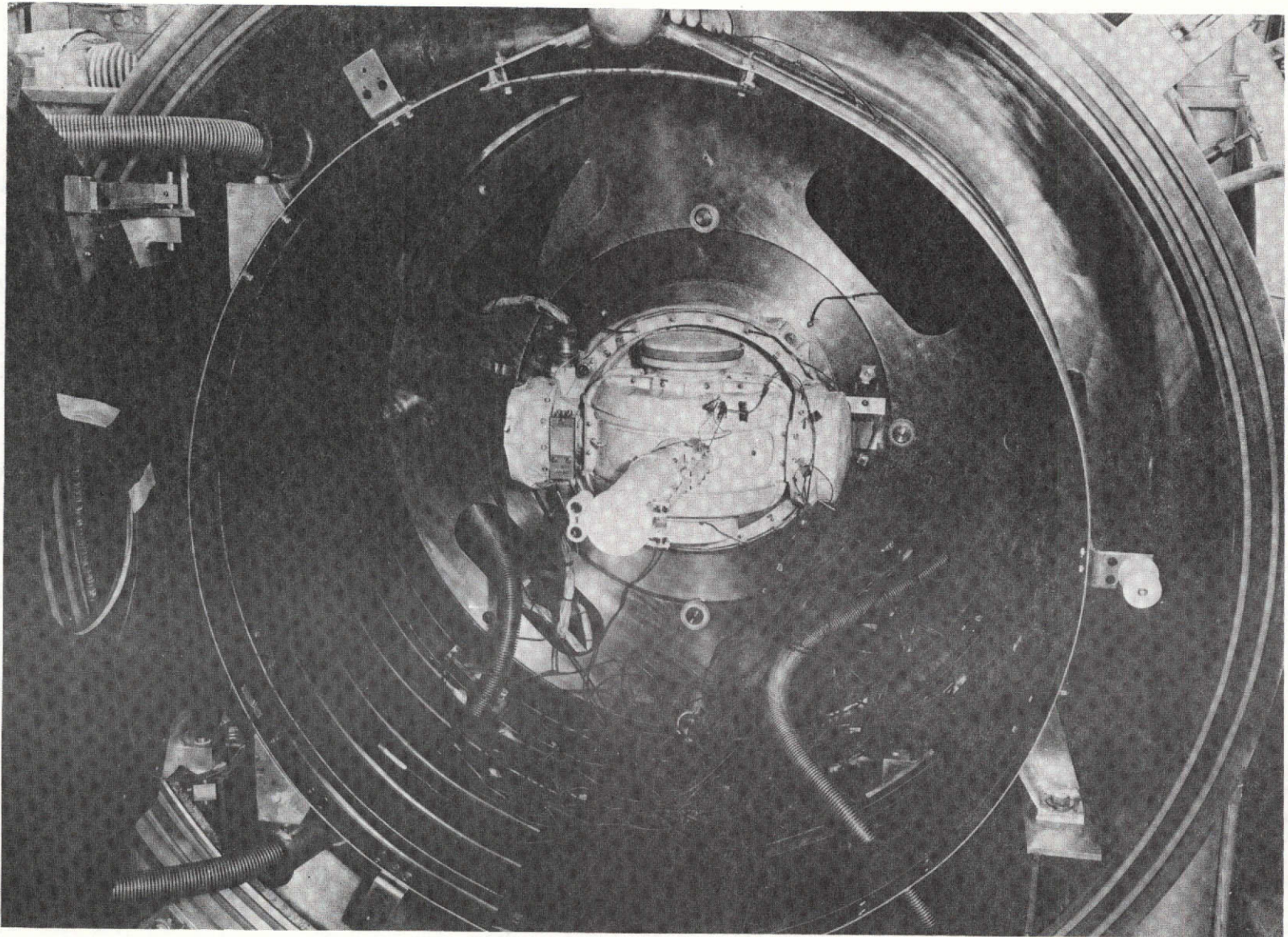
OPTICAL MECHANICAL ASSEMBLY MOUNTED IN
THERMAL VACUUM CHAMBER
FIGURE 4-2
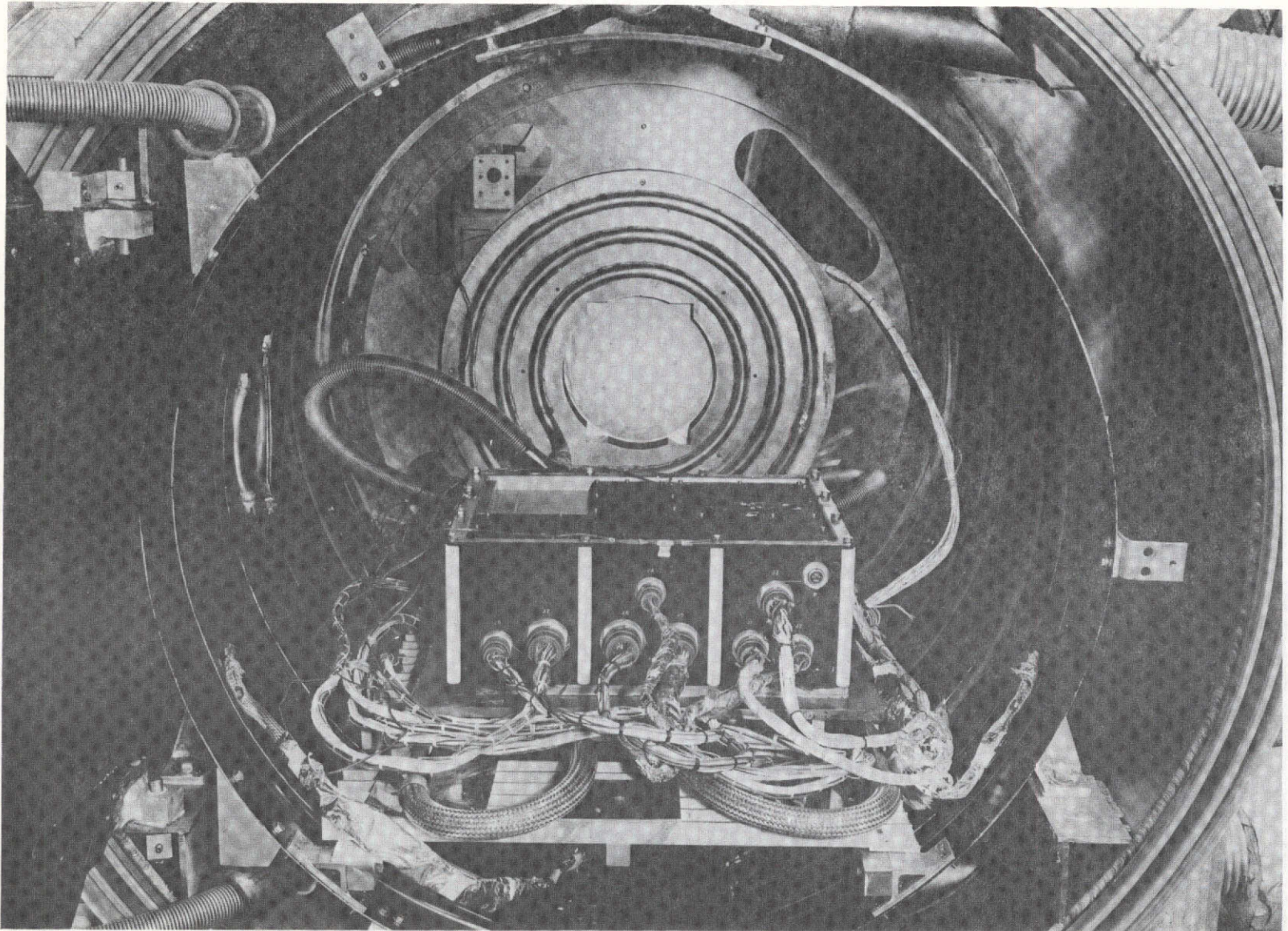
STAR TRACKER ELECTRONICS SHOWN MOUNTED IN
THERMAL VACUUM CHAMBER
FIGURE 4-3

Bendix Navigation & Control Division
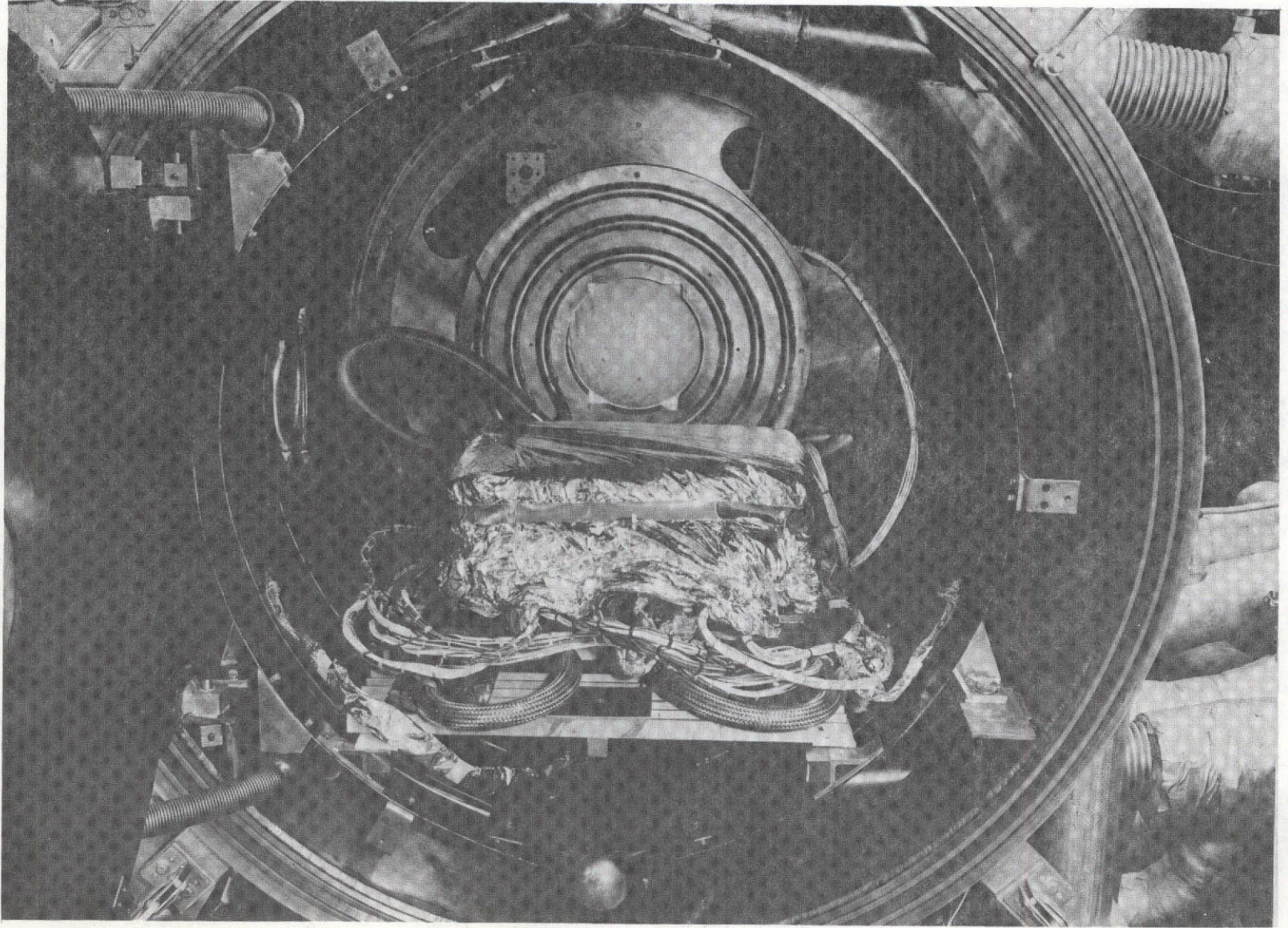
STAR TRACKER ELECTRONICS WITH THERMAL
BLANKET MOUNTED IN THERMAL VACUUM CHAMBER
FIGURE 4-4

Bendix

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Control Division

Qualification testing was resumed beginning with this full functional test, performed per 2124424 (GQTP) 4.2.2. Operation was satisfactory throughout the test and the results were within specified limits.

7) The star tracker was subjected to the vibration test per 2124424 (GQTP) 4.2.9. Following the exposure, inspection revealed no evidence of damage, operation was satisfactory, and function test results were within specified limits.

   Figures 4-5 and 4-6 illustrate the vibration test set-up for the OMA and STE respectively.

8) The star tracker was subjected to the acceleration test per 2124424 (GTQP) 4.2.8. The tests were performed in two parts: A partial exposure in which the OMA and STE were accelerated along the flight axis and in both directions in each transverse axis, and second, a final exposure in which the units were accelerated in the negative direction along the flight axis. Functional tests were performed following the partial exposures and again following the final exposure. Inspections after the tests disclosed no evidence of damage, operation was satisfactory, and the functional test results were within specified limits.
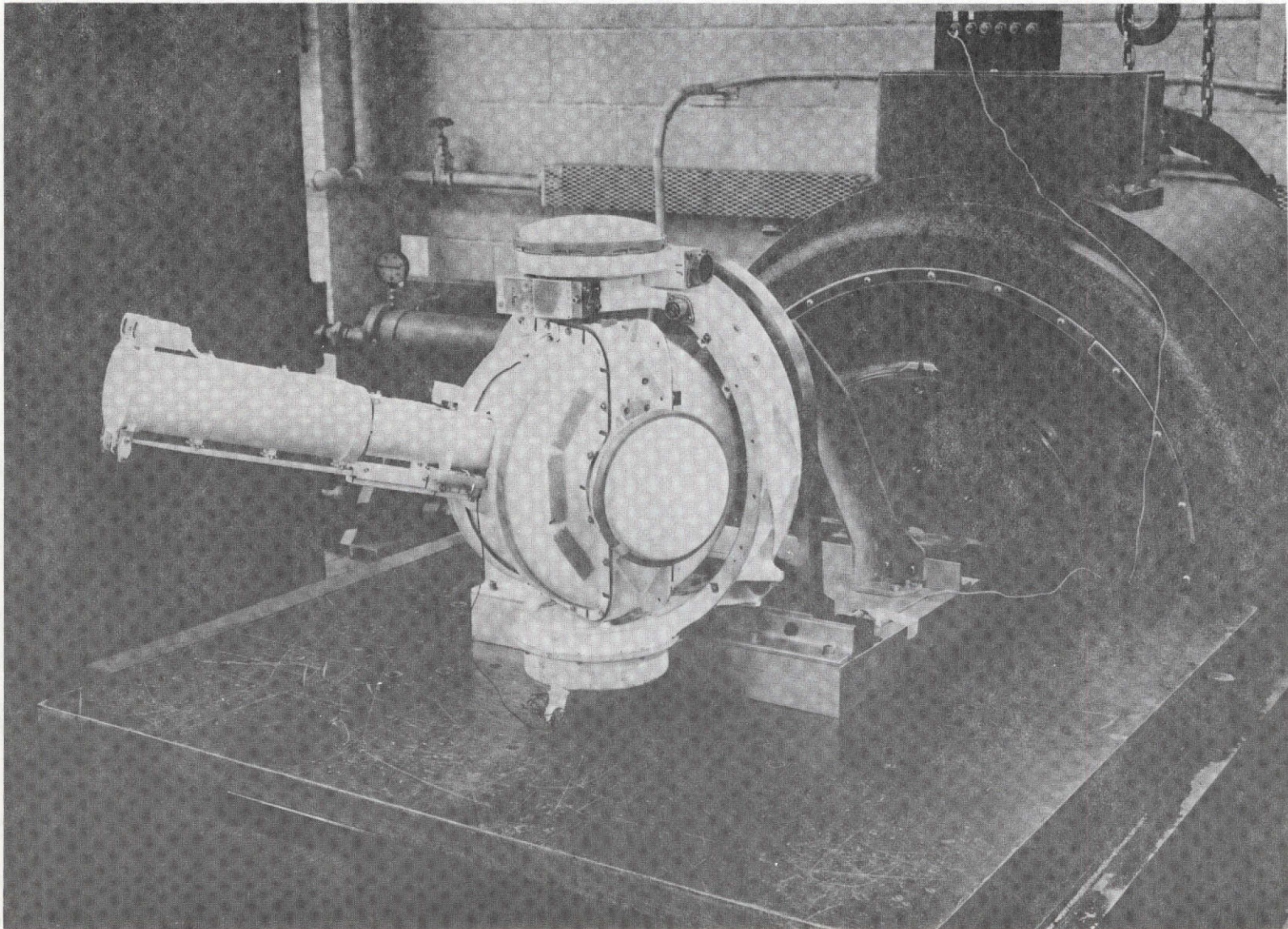
OPTICAL MECHANICAL ASSEMBLY MOUNTED
ON VIBRATION EQUIPMENT
FIGURE 4-5

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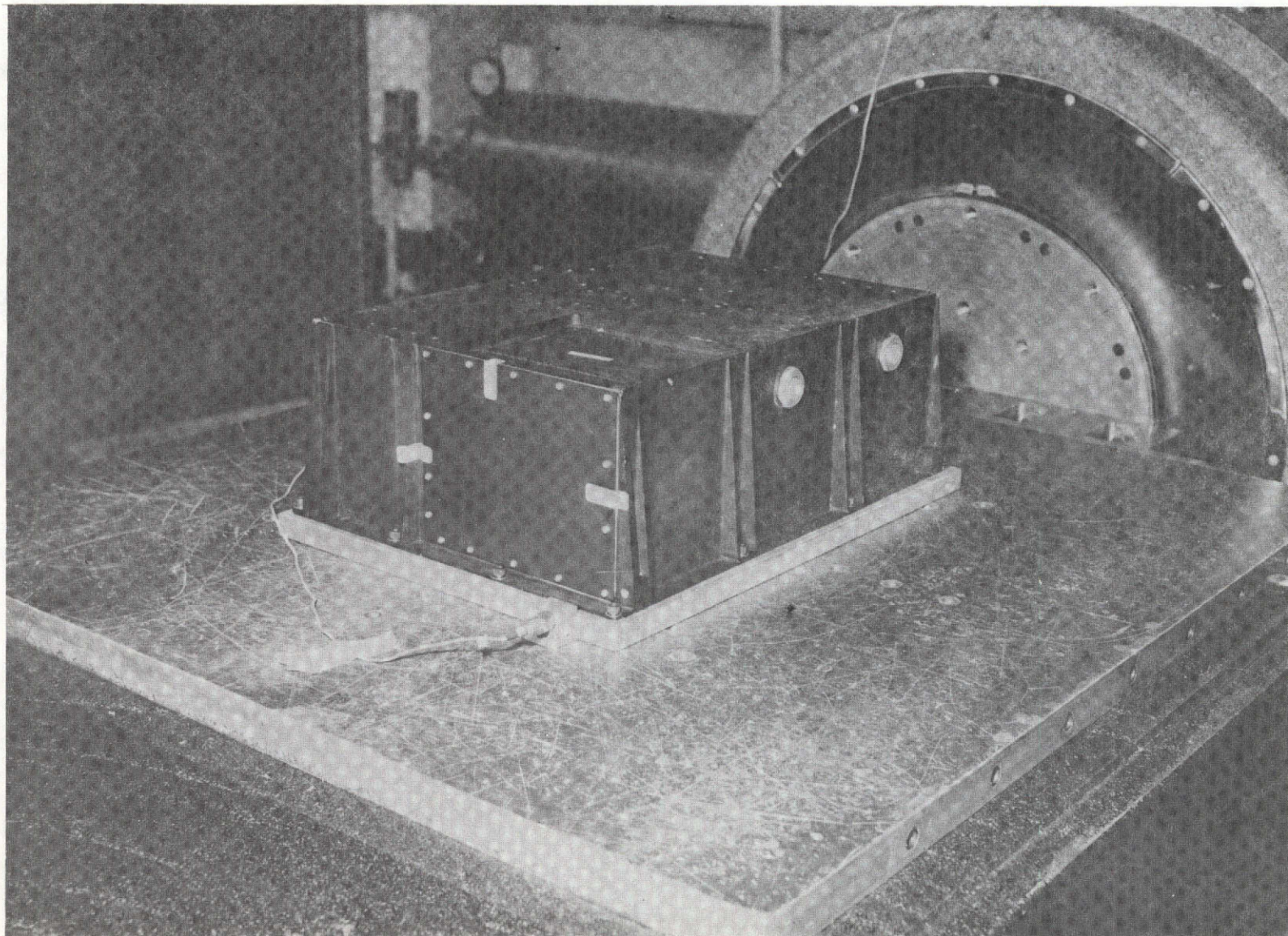
STAR TRACKER ELECTRONICS MOUNTED ON
VIBRATION EQUIPMENT
FIGURE 4-6

9) The star tracker was subjected to the acoustical noise test per 2124424 (GQTP) 4.2.6. Following the exposure, inspection revealed no evidence of damage, operation was satisfactory, and functional test results were within specified limits.

   Figure 4-7 is a photograph of the OMA in the acoustical test chamber.

10) The star tracker was subjected to the thermal vacuum test per (GQTP) 2124424 paragraph 4.2.5.

   During the cold case test, paragraph 4.2.5.2.2b, the STE platen temperature was maintained as specified with the star tracker electronics not energized. However, when the star tracker electronics were energized, the STE platen temperature could not be reduced to a value which would bring the STE down to its specified value of $-15 \pm 3.6^{\circ}F$. Due to this limited low temperature capability of the thermal equipment, the low temperature functional test was begun with the STE at -8 degrees F and completed with the electronics at -3 degrees F. In the worst case then the STE was 8 degrees above the specification limit with the average somewhat less. The thermal vacuum test was continued from this point, with the concurrence of MSFC personnel, with the feeling that the basic intent of the specification had been met, and the knowledge that the unit had yet to go through a more severe thermal-facuum life test. A successful life test was later performed with equipment that maintained the qualification
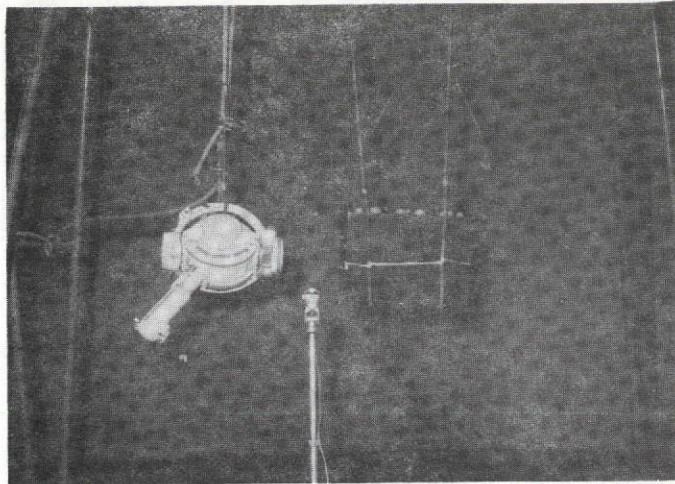
RUN NO. 1
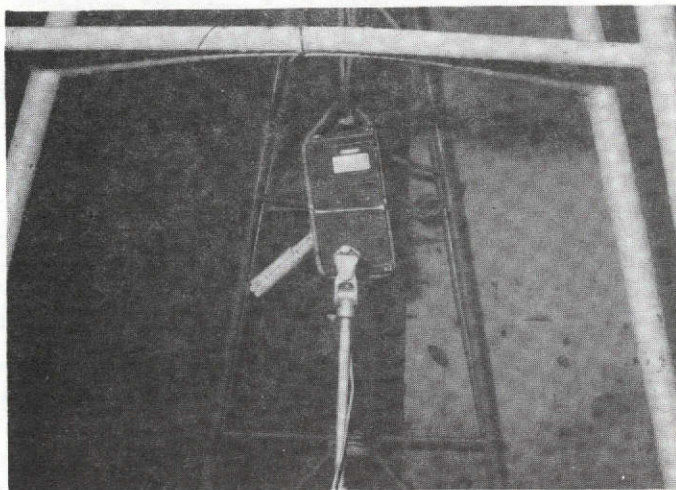
RUN NO. 2
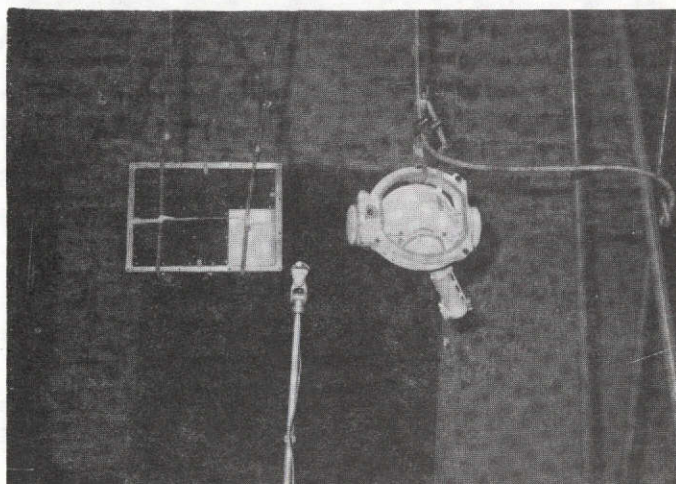
RUN NO. 3

STAR TRACKER AT ACOUSTICAL NOISE FACILITY
FIGURE 4-7

4-14

test cold case environment for 4 days – not a two hour soak plus test time. Additionally, during the cold case and hot case exposures, the telescope movement about the inner gimbal axis was checked throughout its full range but the movement about the outer gimbal axis was checked through a limited range to preclude interference between the tele-scope and test chamber.

Both during and after the thermal-vacuum test ex-posure, functional tests were performed on the tracker system. The functional tests were perform-ed according to the qualification test procedure.

It should be noted that the gimbal accuracy data taken as part of the functional test performed after the thermal-vacuum exposure did not meet the specification limit. For all three stars, the outer gimbal accuracy error was 0.7 minutes RMS and should have been 0.5 minutes RMS or less. It was determined from subsequent testing of other star trackers, that the probable cause of this error was a telescope lens shift. This lens hold-ing mechanism was improved and incorporated into the follow-on trackers.

11) The star tracker was subjected to the circuit tran-sient test per GQTP 2124424 paragraph 4.2.11.

The circuit transients generated by the tracker and its response to transients were within the specifi-cation limits.

A functional test was performed after the initial transient test when the tracker's response to external circuit transients was observed. This test was noted as the final functional test. The results of this test were acceptable as explained in the final functional test, next paragraph. No functional test was performed after the portion of the circuit transient test in which the transients generated by the tracker system were observed. None was considered necessary as this was considered normal star tracker operating procedure.

12) The star tracker was subjected to a full functional test per GQTP 2124424 paragraph 4.2.2 following the completion of the qualification environmental tests.

The data indicates that the unit met the specification limits except for the gimbal accuracy test. In this case the results are similar to the results obtained in the previous function test performed at the conclusion of the thermal-vacuum test. That is, the system gimbal accuracy has not changed from the previous functional test, and for all three stars, the O.G. axis has between 0.6 and 0.7 minutes RMS of error (specification value being 0.5 minutes RMS error or less). The cause of this error being a telescope lens shift which occurred in the thermal vacuum test and discussed in that paragraph.

13) The star tracker was subjected to outgassing tests
per GQTP 2124424 paragraph 4.2.3 by NASA at the
George C. Marshall Space Flight Center in December
1971.

The Navigation and Control Division was infomred
by MSFC technical personnel that the test results
were satisfactory.

Following the outgassing test, the star tracker was
returned to BNCD where a reduced functional test
was performed. These tests were per GTSP 2124427,
sections 4.3.1, 4.3, 4.3, 5.5, 5.6, 5.7, 5.8, 5.9,
5.10 reduced, 4.11 and 5.12. The results of the
test within specified limits, indicating that no
damage or deterioration to the unit's performance
occurred due to subjecting the hardware to the out-
gassing test.

In summary then with the exception of the low temperature
portion of the thermal vacuum exposure, the Star Tracker
system was successfully subjected to the environment
portions of the qualification test. Due to thermal
vacuum chamber limitations, the electronics package was
tested at about five degrees F above the specified cold
temperature limit; the test was accepted by MSFC. The
Star Tracker System operation during the environmental
exposures was satisfactory, and except in the case of
electromagnetic interference, results were within speci-
fied limits. During the electromagnetic interference
tests, generated and conducted interference in excess
of permissible limits was measured. Increases in the
permissible levels of interference were requested and
granted by MSFC.

Functional operation of the Star Tracker System was
satisfactory after each environmental exposure except
for the slight increase in outer gimbal accuracy error
noted after thermal vacuum testing. Subsequent testing
on other Star Tracker Systems has pointed to a loose
telescope lens holding mechanism as the cause of this
error.

The Star Tracker System completed its qualification
testing program without any functional damage or
deterioration to the unit.

The Guidance Systems Division concluded that the Star
Tracker, (the Optical Mechanical Assembly and the Star
Tracker Electronics) conformed to the contractual de-
sign requirements as demonstrated by the satisfactory
completion of the qualification test, and recommended
that the star tracker be accepted as qualified hardware.

SECTION 5

5.0 RELIABILITY

During the course of theprogram a Failure Mode Effects and Criticality Analysis (FMECA) was performed on the ATM tracker in accordance with NASA Reliability Publication 250-1.

5.1 Summary of Results

Criticality Number, $C_R = (\lambda_{N_1} t + \lambda_{N_2} t_m) 10^6 = 172,680$

Reliability Index, $R(t) = e^{-(\lambda_{N_1} t + \lambda_{N_2} t_m)}$ = 0.842

MTBF, $1/\lambda_T$ = 10,417 Hours

Failure Rate (TOTAL)**, λ_T# = 96.0 PPMH*

Failure Rate (NET)***, $\lambda_N = \lambda_{N_1} + \lambda_{N_2}$# = 47.8

Factored Mission Time (T)Δ = 3,600 Hours

Total Mission Time (t_m) = 5,760 Hours

A detailed listing of individual block failure rates and criticality numbers is included in Sections 6 and 7, respectively of the original FMECA report.

Notes and Definitions:

N_1 = Failure Rate (net) of items that are operational during a time period equivalent to t ≈ 47.6 PPMH.

N_2 = Failure Rate (net) of items that are operational during the total mission time (t_m) ≈ 0.24 PPMH.

\# Includes equivalent failure rate of redundant items.

Δ Refer to Page 7-2 of the original FMECA report.

* Failure Rate (Total) unadjusted for redundancy:

123.4 PPMH

** Sum of Block Failure Rates (TOTAL):

$$X = n_2$$

$$Y = n_1$$

$$\lambda_T = \sum_{\substack{Y=1 \\ X=1}} [\; F_{(Y)} \;]\; (X)$$

*** Sum of Block Failure Rates (NET):

$$X = n_2$$

$$Y = n_1$$

$$\lambda_N = \sum_{\substack{Y=1 \\ X=1}} [\; \beta c_{(Y)} \; F_{(Y)} \;]\; (X)$$

Where F is equal to the failure rate associated with
block failure effect (Y), n_1 is equal to the number of
failure effects (Y) of Block X; n_2 is equal to the
number of blocks in the ATM Star Tracker, and ßc is
the Beta Factor applied to F, which is described on
Page 4-9 of the original FMECA report.

APPENDIX I

HISTORICAL SUMMARY OF PROGRAM

The following is a brief summary of the program. More
detailed historical notes may be found in the monthly
progress reports.

September 1968 – Program start – Program control procedures set
up. Star tracker vehicle interface definition
near completion. Optical encoder specifications
released. Test equipment requirements established.

October 1968   – Interface definition basically completed. System
block diagrams and descriptive layouts submitted.
Optical encoder order released. Gimble casting
drawing released. Telescope schematics and
casting drawings nearing completion. Basic
digital logic unit (DLU) design completed. Started
design concept phase of final acceptance test
equipment.

November 1968 – Design review conducted at NASA MSFC on November 20,
preliminary design review conducted at Bendix
November 26, and encoder design review conducted
at Baldwin. Telescope casting drawing released.

December 1968 – Interface requirements defined in new design
areas. Continuation of sunshade shutter and
encoder design. Design of mode selector module
initiated. Many telescope detail assembly draw-
ings released. Sun and earth sensor drawings
started. Test equipment workmanship standard
approval received from NASA.

January 1969 — With the exception of a few drawings, telescope electronic drawings have been completed. Star tracker electronics (STE) "floor plan" and out-line completed and submitted to NASA for review. Acceptance Test Plan and Final Check reviewed at NASA-Bendix. Telescope casting pattern and frame and machining drawings completed. Purchase orders released for all commercial test equipment used in final checkout consoles except for the wattmeter and power supplies (DC).

February 1969 — Pin functions between the vehicle and the star tracker electronics (STE) and the STE and the optical mechanical assembly (OMA) defined. Shade-shutter concept finalized. Engineering model en-coder tested successfully. An engineering model of the sun sensor was constructed. Initial gimbal housing and telescope housings have been cast. Initial outgassing test on wet-lube bearings successfully completed. Heater power require-ments determined. Additional schematic diagrams released.

March 1969 — Updated layout and block diagram drawings submitted to NASA for review. Preliminary thermal analysis for heaters completed. Telescope and gimbal castings were heat-treated. Sun shade shutter-sensor layout completed. Encoder mounting assembly parts were completed. Drawing revisions for heater implemen-tation were completed. Several test specifications and printed circuit boards were completed. Shutter electronic schematic and mode selector design were completed. Servo loop layouts were completed. Mode

selector, input interface and ac to dc converter design completed. All final acceptance test equipment commercial test instruments are on order. Design of in-process test equipment almost complete. Fabrication on most test equipment completed or started.

April 1969 — Stress and thermal problems at the star tracker mounting bracket interface defined. Two sets of encoder electronic circuit boards were completed. Machining of telescope casting about 25 percent complete. Two gimbal castings released for machining. All telescope electronics printed circuit boards completed. Ac to dc converter testing successfully completed. Two test stand panels (final acceptance test equipment) were submitted to NASA for design approval. Modification of existing Bendix telescope module test stand started. Fabrication of telescope electrical test station completed. Fabrication of encoder electrical test station interconnect cables completed. Telescope test fixture fabricated. Encoder test fixture completed.

May 1969 — Design review conducted at NASA MSFC on May 8. Encoder mounting assemblies completed and shipped to Baldwin. Phototubes for flight 1 and 2 systems received. All Bendix final acceptance test stand panels approved by NASA.

June 1969   – Tube and HVPS modules completed and assembly of tube HVPS assembly started. Three telescope housings machined and ready for painting. Vibration analysis finalized and documented. The three ATM Star Tracker Final Check-out Consoles were released to fabrication. The following in-process test equipment has been completed. Telescope Module Test Station, Telescope System Electronics Test Station, Encoder Electrical Test Station, Telescope Test Fixture, Motor and Tachometer Test Fixtures, and Encoder Test Fixture.

July 1969   – Critical Design Review conducted at NASA MFSC on July 22. Preliminary Acceptance Test Procedure completed and submitted for review. Earth sensor prototype built. Four encoder hub assemblies shipped to Baldwin. All mechanical design drawings released. All Telescope Electronics Assembly drawings released. Vibration and thermal stress analysis completed. Thermal model of Optical Mechanical Assembly (OMA) completed and documented.

August 1969   – Adaption of star simulator computer program completed. Procedures for earth and sun sensor testing completed. Studies of proposed phototube and pivot life tests completed. Telescope electronics completed and under test. All STE drawings released to production. OMA frame thermal interface defined. Analysis of STE circuit boards completed.

September 1969 – Qualification and acceptance testing of the prototype encoders successfully completed. Star standard received from Goodard Space Flight Center (GSFC).

Three telescope housings completed. Prototype
gimbal machined. Telescope electronics success-
fully tested over temperature range. Inner and
outer.loop amplifier cards built and tested. Three
FCO electronic consoles, without intercept boxes
are 95 percent assembled. Intercept box and
associated cable design has begun. The STE module
test stand is completed. The STE system test
stand is 80 percent completed. Mechanical test
stands are complete except for the end stop micro-
switches. Master Test Fixture and Telescope Align-
ment Fixture 75 percent complete. Vibration and
Thermal Vacuum fixture design completed. Fabrication
of fixtures started.

October 1969   – Encoder-frame compatability tests for both the
Vanasil frame and A390 frame completed. Proto-
type gimbal ready for OMA assembly. Final test
completed on three final acceptance test stands.
Some STE modules for prototype completed.

November 1969   – Five optical shaft encoders have passed their
acceptance test and have been delivered to Bendix.
Prototype gimbal assembly buildup proceeding satis-
factorily and telescope assembly is being prepared
for installation. Lube-life rig ready to be assembled.
Test equipment checkout on three final acceptance test
stands completed.

December 1969   – Five additional optical shaft encoders ready for
acceptance test. Prototype gimbal assembly build-
up and telescope testing progressing satisfactorily.
Lube-life rig approaching final assembly. Photo-
type sunshade and shutter mechanism completed and
checked out.

January 1970   – Prototype telescope electronics bench tested and adjusted. Prototype STE and OMA married and tested extensively by engineering. Five additional optical shaft encoders successfully passed acceptance tests Life-lube rig assembled. (See Figure A-1). One 130F751 ATM Final Checkout Console checked out with prototype star tracker. Three OMA intercept boxes received and are being checked out.

February 1970   – Prototype ATM Star Tracker engineering tests approaching completion. ATM Star Tracker gimbal servo loops modified. Tachometer and torquer magnetic cross talk problem eliminated.

March 1970   – ATM Star Tracker electronic tracking loops modified to increase response. Shutter motor drive electronics and mechanism modified to prevent relay arcing and to provide smoother travel for shutter. ATM Star Tracker Final Checkout Console 130F751 SN1 ready for checkout with Star Tracker system and correlation tests with SN3 test stand. ATM Star Tracker Final Checkout Console SN3 in Star Tracker final test area completely checked out with the Star Tracker System.

April 1970   – ATM Star Tracker prototype acceptance tested and delivered. ATM Star Trackers SN2 and SN3 sub-assemblies being tested. OMA life lube rig completed and delivered. ATM Star Tracker FCO Console 130F75-1 -1 SN1 tested, inspected and shipped to MFSC. Started to update SN2.
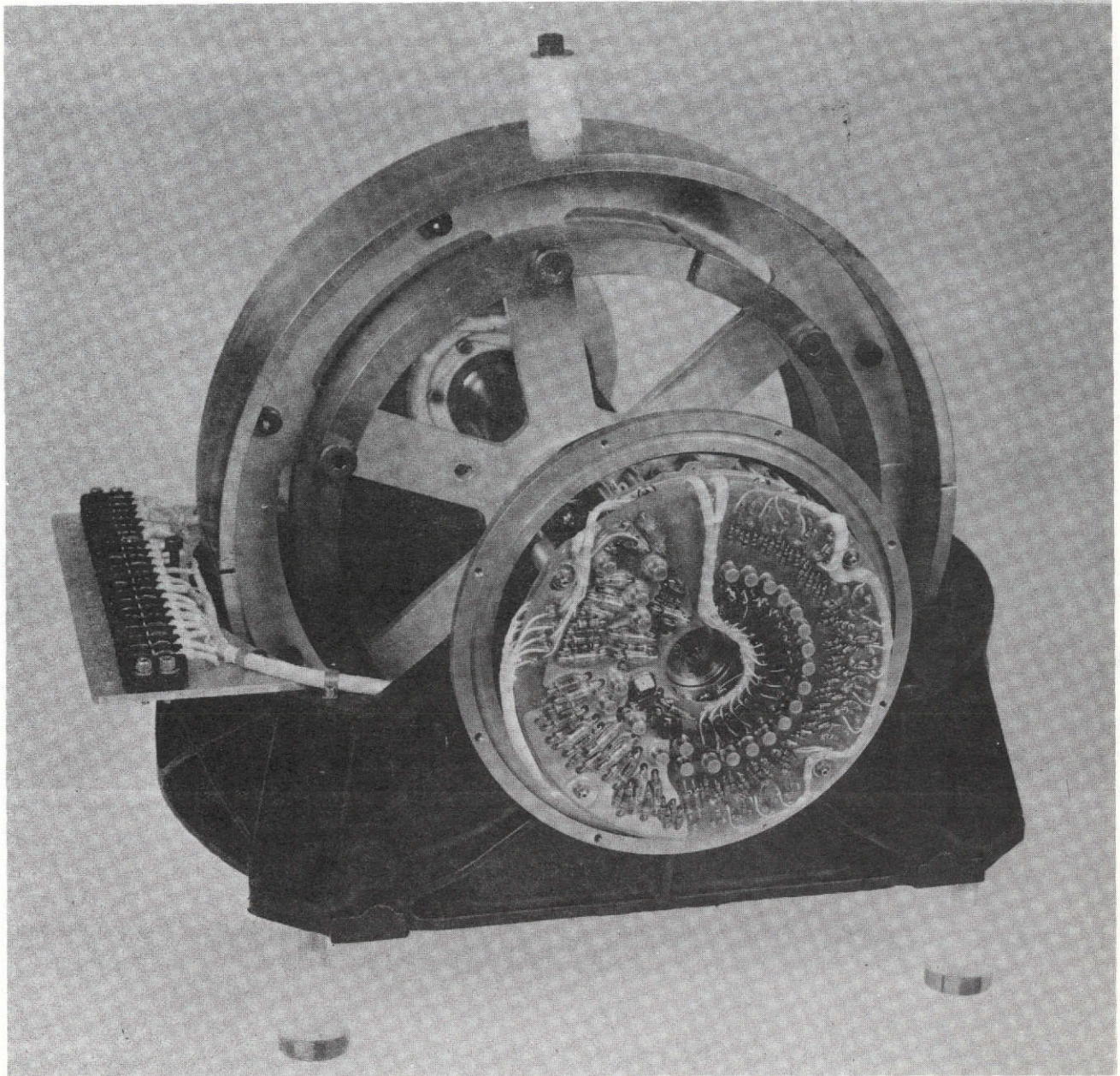
FIGURE A-1

A-7

May 1970   – ATM Star Tracker SN2 and SN3 subassembly test-
ing near completion. Variable dark current
problem isolated and identified. Shutter
mechanism undergoing redesign. Star Tracker
FCO Console 130F751-1 SN2 updated. Three sets
of log books for FCO consoles completed.

June 1970   – ATM Star Tracker SN4 undergoing manufacturing
checkout calibration and alignment. Tube HVPS
design finalized (with respect to high voltage
design). Telescope internal pressure tests
completed. Telescope electronics and STE for
system number four completed. Solar impingement
cables (used to interface the Star tracker system
with the General Electric solar impingement chamber)
designed and fabricated.

July 1970   – ATM Star Tracker SN2 ready for manufacturing check-
out calibration and alignment. SN2 tube   HVPS
assembled and installed in OMA. Shutter life lube
rig completed. All three ATM Star Tracker FCO
consoles now operational.

August 1970   – Manual mode altered to eliminate response to
structural 170 Hz resonance. Telescope elec-
tronics video amplifier altered to eliminate
threshold problem. Hold mode changed to
eliminate a 10 Hz oscillation. Telescope
shade motor drive circuitry modified to elimi-
nate relay arc over.

September 1970 — ATM Star Tracker SN2 system being prepared for manufacturing checkout calibration and alignment. Telescope shade motor drive circuitry modified to eliminate transients generated by the motor.

October 1970 — Redesigned phototube undergoing installation. ATM Star Tracker SN3 system being prepared for manufacturing checkout calibration and alignment. Telescope shade mechanical drive modified to prevent shade from opening during launch vibration. Shutter close command logic altered to prevent incorrect updating of the DLU upon entering the hold mode. ATM Star Tracker SN2 system acceptance test completed.

November 1970 — ATM Star Tracker SN3 system completed manufacturing checkout calibration and alignment and is undergoing acceptance test. ATM Star Tracker SN4 ready for manufacturing checkout calibration and alignment.

December 1970 — ATM Star Tracker SN3 system completed acceptance testing and is being prepared for qualification testing. ATM Star Tracker SN4 system completed first stage of manufacturing checkout, calibration, and alignment.

January 1971 — ATM Star Tracker SN4 OMA and STE system checkout calibration, and alignment completed. Methode connector rework completed for SN3 and SN5 STE.

February 1971 — ATM Star Tracker SN4 system acceptance test completed and shipped to NASA. ATM Star Tracker SN3 system transformer changed, connector and encoder bellows reworked and final gimbal alignment completed. The system is ready for qualification test. ATM Star

Tracker SN5 system ready for system checkout alignment and calibration.

March 1971 — ATM Star Tracker SN3 OMA gimbal alignment completed. SN3 system qualification test program started.

April 1971 — Corrected misalignment of field-scribe line of deflection coil. Vendor agreed to replace coils having misaligned field-scribe lines.

May 1971 — Tube-HVPS for qual system SN3 has completed third stage potting. Tube - HVPS for system SN5 has been completed.

June 1971 — Build and thermal vacuum testing for SN3 tube-HVPS completed. Final build of SN3 OMA and optical axis alignment completed. Final temperature testing of SN5 earth sensor completed.

July 1971 — ATM Star Tracker SN3 assembled aligned and acceptance tested. Qualification testing of SN3 started. ATM Star Tracker SN5 system checkout and alignment started. SN6 sun sensor completed.

August 1971 — Qualification test of ATM Star Tracker SN3 in progress. Alignment of ATM Star Tracker SN5 interrupted due to misalignment of gimbal orthogonality. Misalignment corrected. Thermal vacuum testing of ATM Star Tracker SN6 tube HVPS terminated due to arcing caused by broken lead. Tube lead repaired.

September and October 1971 — Qualification test of ATM Star Tracker SN3 in progress. Build and test of ATM Star Tracker SN3 replacement tube - HVPS completed. Acceptance testing of ATM Star Tracker SN5 completed.

November and — Qualification test of ATM Star Tracker SN3 completed.
December 1971   ATM Star Tracker SN5 shipped to MSFC but subsequently
                  returned to Bendix for modifications. Primary build
                  and alignment of ATM Star Tracker SN6 completed.
                  ATM Star Tracker SN4 exposed to 2 weeks of low temper-
                  ature vacuum without problems.

January and — ATM Star Tracker SN5 modified, tested and reshipped
February 1972   to MSFC. ATM Star Tracker SN6 built and under test.
                  Low temperature tests completed on ATM Star Tracker
                  SN4. The unit was shipped to MSFC.

June, July — OMA SN0003 14 day life test completed. Unit shipped
and August 1972   to MSFC. OMA SN0004 returned to Bendix and updating
                  to latest configuration started. OMA SN0005 repaired
                  at Bendix and shipped to MSFC.

September — Star simulator recalibrated at Houston Manned Space
Through   Flight Center. ATM Star Tracker SN6 retested and
December 1972   found to be within specifications. ATM Star Tracker
                  SN4 retrofit completed.

January — Intermittent oscillation experienced in SN006 STE.
Through   Problem trouble shooting performed. Failure traced
March 1973   to Initial Position register card by test and
                  analyses. Cause of failure confirmed by x-ray of
                  microstick which showed broken lead (ground).

April — Rebuild and retrofit of SN4 completed required
Through   because of vamistor resistor replacement. Acceptance
June 1973   testing completed. Unit flown aboard Skylab vehicle.

July — Rework of SN5 OMA initiated. Spare cards manufacture
Through   in progress.
September 1973

October
Through
December 1973

    – Rework of SN5 OMA completed.

January
Through
February 1974

    – System SN6 successfully passed acceptance test.

APPENDIX II

II-0   DESIGN CHANGES

II-1   ANGLE OF GIMBAL TRAVEL
         Angle of gimbal travel change from $\pm$ 80 to $\pm$ 85 to
         $\pm$ 87 degrees.

II-2   TELESCOPE ELECTRONICS CHASSIS
         Chassis for telescope electronics revised to provide
         an environmental seal and add a separate connector
         for disengaging sensor signals.

II-3   INCREASED TORQUE
         A requirement for increased torque has necessitated
         a change in the torquer motor. A type T2201 torquer
         with a dc resistance of 127 ohms was used to deliver
         30 ounce-inches of torque.

II-4   THRESHOLD LEVEL
         The threshold level of the video amplifier was lowered
         to include the new target star α-CRUS.

         A.   White Paint Substitute
              Pyromark white thermal control paint had been
              approved for use on the OMA wherever 4-13G is
              specified. This coating was applied and vacuum-
              baked at Bendix.

II-5   BLACK PAINT SUBSTITUTE
         Optical black paint 3M-101C10 substituted for Parson's
         Black.

II-6   INTERFACE PROBLEM

Digital logic unit (DLU) interface and conditioning
card redesigned to avoid potential interface problem
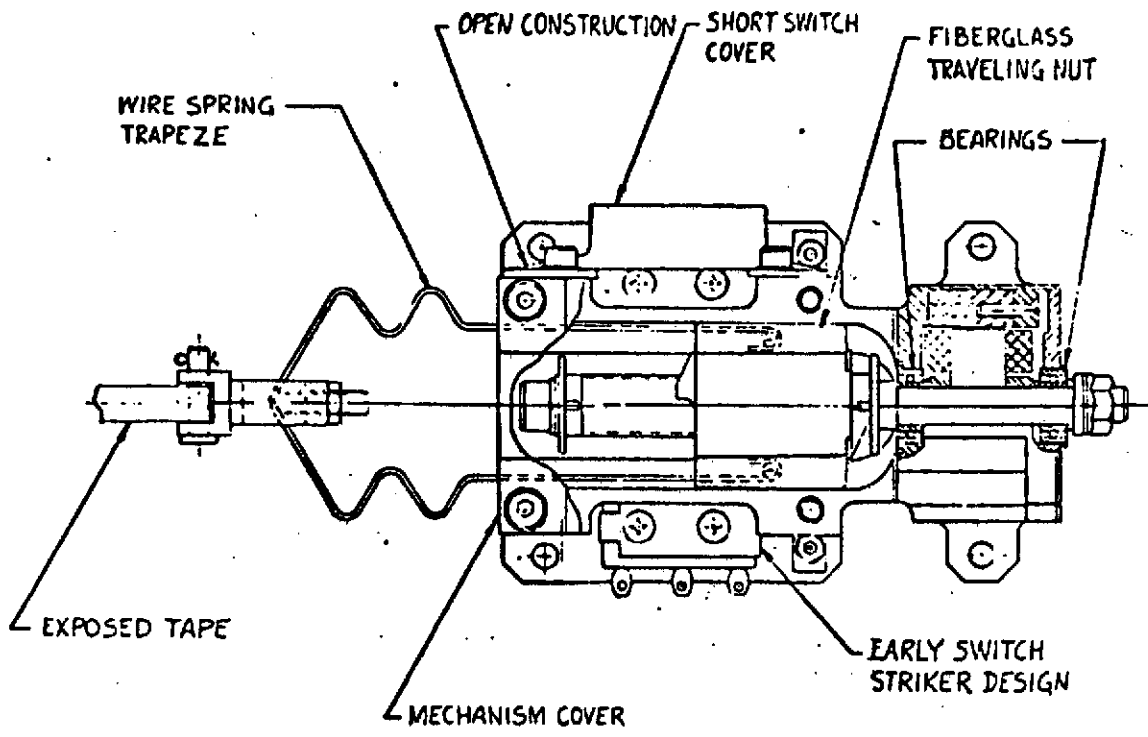between the DLU and mode selector logic.

II-7   BANDWIDTH INCREASE

The bandwidth of theelectronic tracking loop, which
centers the instantaneous field of view on the star
line of sight was increased from 50 radians to 150
radians to improve response. Prior to redesign, the
star was lost during the acquisition cycle due to the
failure of the instantaneous field to properly follow
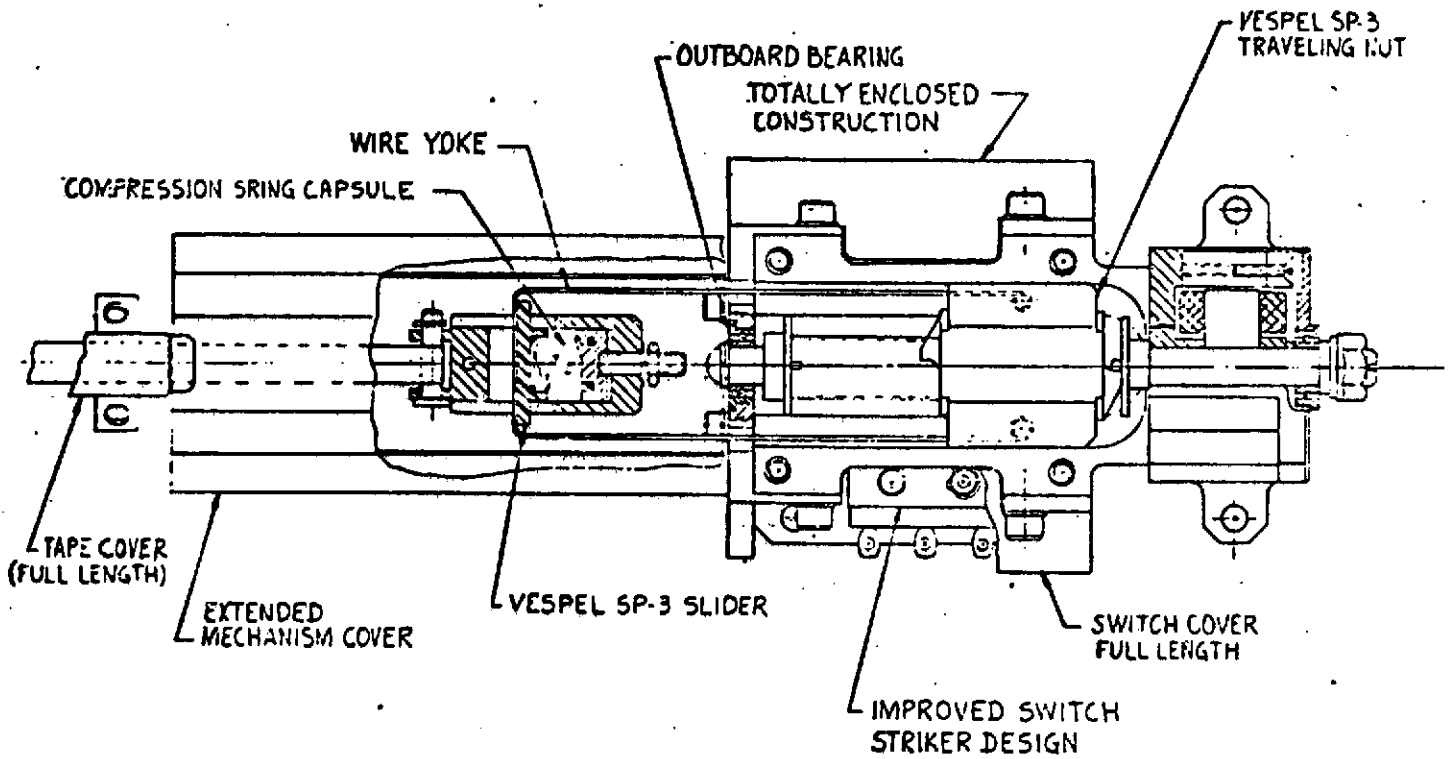up the line of sight.

II-8   SUNSHADE AND SHUTTER MECHANISM

The shutter mechanisms were fitted with covers to
completely shroud all operating parts including the
tape. As part of the modification, one jackscrew
bearing was relocated to reduce the possibility of
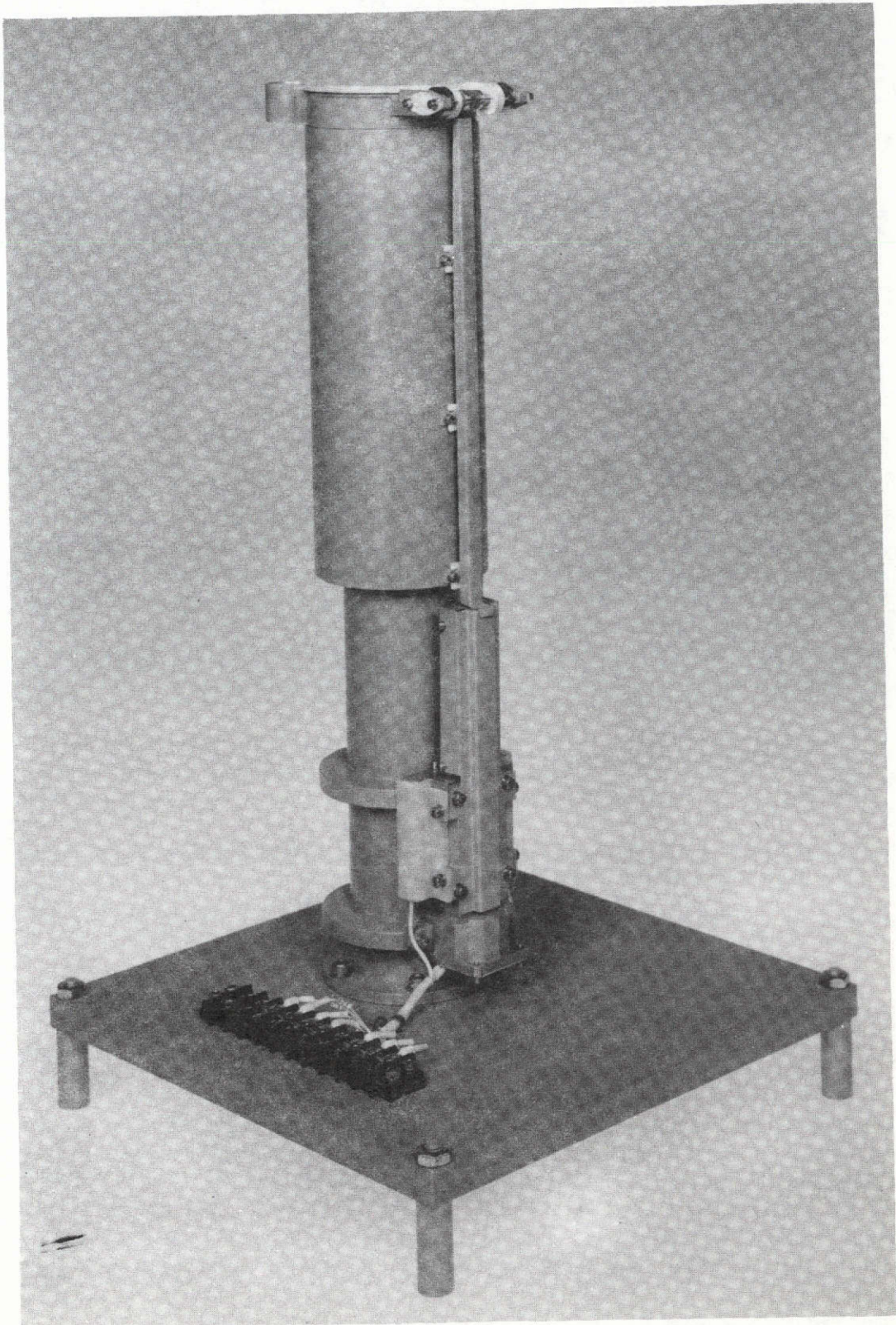shaft runout. Refer to Figures II-1 through II-3.

Shutter Test Rig was rebuilt with new 32 threads per
inch jackscrew and nut combination, new spring, and
retainers. A new larger dia. shaft was fabricated
and installed at shutter end. This new design pro-
vided a greater mechanical advantage thus allowing
a greater force to be applied at the shutter without
increase of power. Test rig was subjected to high
and low level random vibration test and shutter re-
mained closed.

WIRE SPRING
TRAPEZE

OPEN CONSTRUCTION — SHORT SWITCH
COVER

FIBERGLASS
TRAVELING NUT

BEARINGS

EXPOSED TAPE

MECHANISM COVER

EARLY SWITCH
STRIKER DESIGN

ORIGINAL SHUTTER MECHANISM
FIGURE II-1

REVISED SHUTTER MECHANISM

FIGURE II-2

SUNSHADE AND SHUTTER MECHANISM
FIGURE II-3

A2-5