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STAR TRACKER FOR THE APOLLO TELESCOPE MOUNT

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The star tracker for the Apollo Telescope Mount (ATM) has been designed specifically to meet the requirements of the Skylab vehicle and mission. The functions of the star tracker are presented, as well as descriptions of the optical-mechanical assembly (OMA) and the star tracker electronics (STE). Also included are the electronic and mechanical specifications, interface and operational requirements, support equipment and test requirements, and occultation information. Laboratory functional tests, environmental qualification tests, and life tests have provided a high confidence factor in the performance of the star tracker in the laboratory and on the Skylab mission.

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SUMMARY

The star tracker for the Apollo Telescope Mount (ATM) has been designed specifically to meet the requirements of the Skylab vehicle and mission. The functions of the star tracker are presented, as well as descriptions of the optical-mechanical assembly (OMA) and the star tracker electronics (STE). Also included are the electronic and mechanical specifications, interface and operational requirements, support equipment and test requirements, and occultation information. Laboratory functional tests, environmental qualification tests, and life tests have provided a high confidence factor in the performance of the star tracker in the laboratory and on the Skylab mission.

INTRODUCTION

The functions of the star tracker for the ATM are to provide celestial position inputs (with respect to the sun, earth, and spacecraft) for calculating the vehicle roll reference and to initially provide an aid for manual attitude alignment about the vehicle Z axis. Vehicle roll reference is determined about the experiment pointing control axis with respect to solar north. Star tracker gimbal angle positions are one set of parameters required by the ATM digital computer (ATMDC) for the calculation.

The ATM star tracker design provides for manual and automatic search and track modes for locating and tracking suitable stars. Target stars will be Canopus (primarily), Achernar, and Alpha Crux. Star tracker subassemblies are the OMA and the STE.

The OMA (Fig. 1) consists of a refractive telescope, photomultiplier tube detector, and telescope electronics with a high voltage power supply (HVPS) mounted on a double gimbal suspension. Starlight is detected through the baffled sunshade into the telescope lens, wedge reflectors, and the photomultiplier tube aperture. A sun sensor and earth albedo sensor are mounted on the end of the sunshade. Signals are provided from these sensors to open or close the shutter. The shutter will be closed automatically when the telescope pointing direction approaches 0.78 rad from the sun, 8.7×10^{-2} rad from the earth albedo, or close to an equivalent bright reflecting object. The telescope electronics is located adjacent to the photomultiplier tube and consists of a video amplifier, scan amplifier, sweep generator, demodulator, raster scan circuits, and HVPS. Inner and outer gimbal

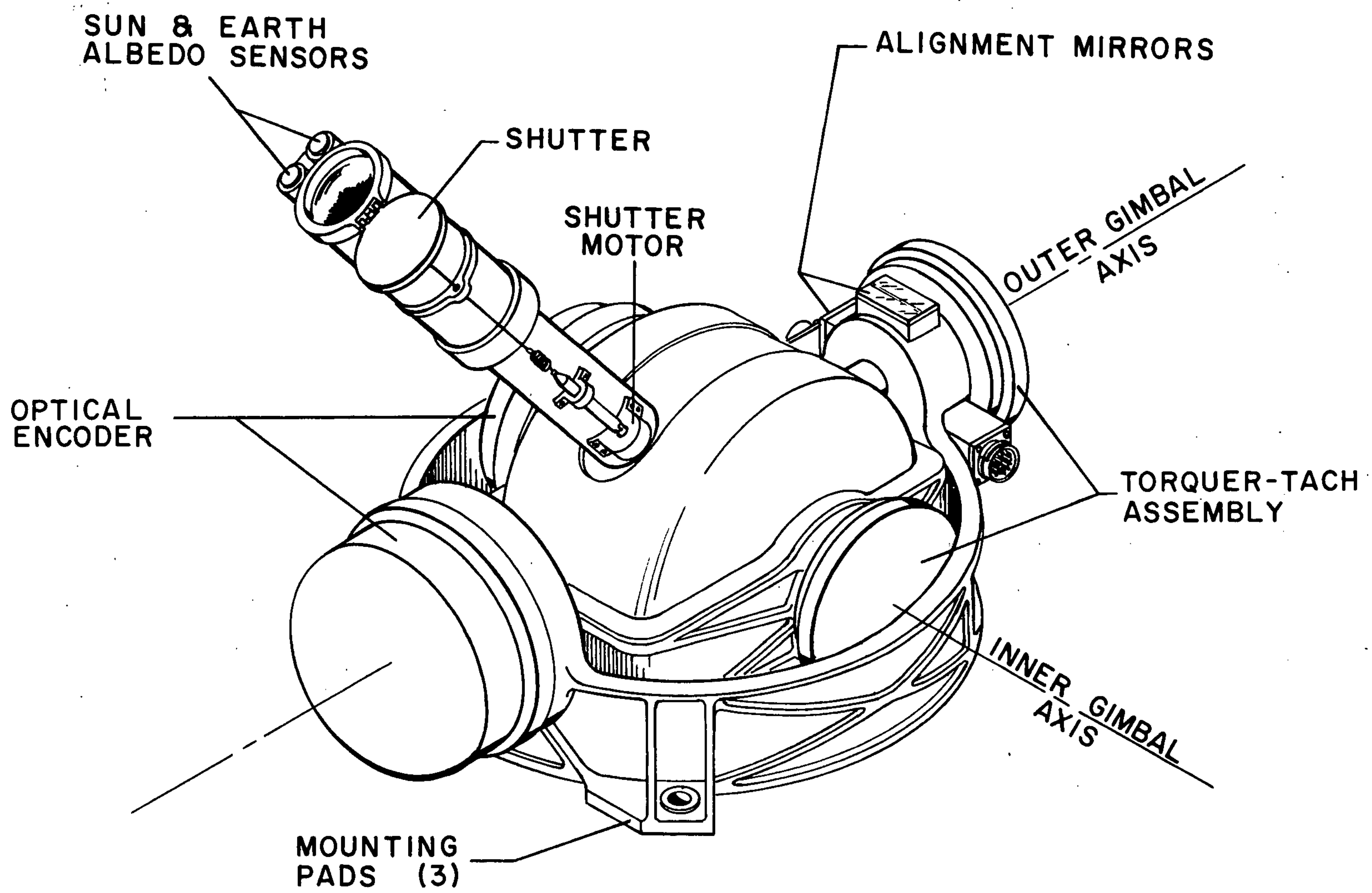

Figure 1. Star tracker optical-mechanical assembly.

pivots contain a torquer-tachometer assembly and an encoder assembly. The torquer-tachometers provide the gimbal servo control and the encoders provide the gimbal position readout. The complete gimbal assembly is supported with a three-point mounting frame.

The STE assembly (Fig. 2) contains servo control circuits, power supplies, ac to dc converter, digital logic unit, mode selecting circuits, shutter drive amplifiers, and auxiliary electronics. All star tracker input-output functions to other systems are interfaced in the electronics assembly. A functional block diagram is shown in Figure 3.

TECHNICAL SPECIFICATIONS

Design requirements for the ATM star tracker are based upon daylight tracking capabilities for a 231-day mission (with 140 days manned) at an altitude of 435 km. The system is designed for astronaut participation and is capable of searching, acquiring, and tracking the reference star automatically after being initiated manually. It is anticipated that Canopus will be available as the target star from 90 to 100 percent of the mission time; this will depend upon the launch hour and day. However, the alternate reference stars, Achernar and Alpha Crux, may be tracked with no degradation in operations.

System Specifications

	Weight (kg)	Size (m)	Power Dissipated (W)
OMA	18	0.43 X 0.32 X 0.53	30.36 (max) 8.6 (av) 20 (heaters)
STE	10	0.47 X 0.29 X 0.16	18.7 (max) 15.1 (av)

Gimbal Specification

Gimbal freedom: Outer ± 1.51 rad; inner ± 0.70 rad.

Gimbal readout: Digital – Serial binary to ATMDC; parallel binary to telemetry.

Gimbal position resolution: 145 μrad (for ATMDC and telemetry); 290 μrad (for ATM control and display).

Gimbal position accuracy: ± 145 μrad (1 sigma).

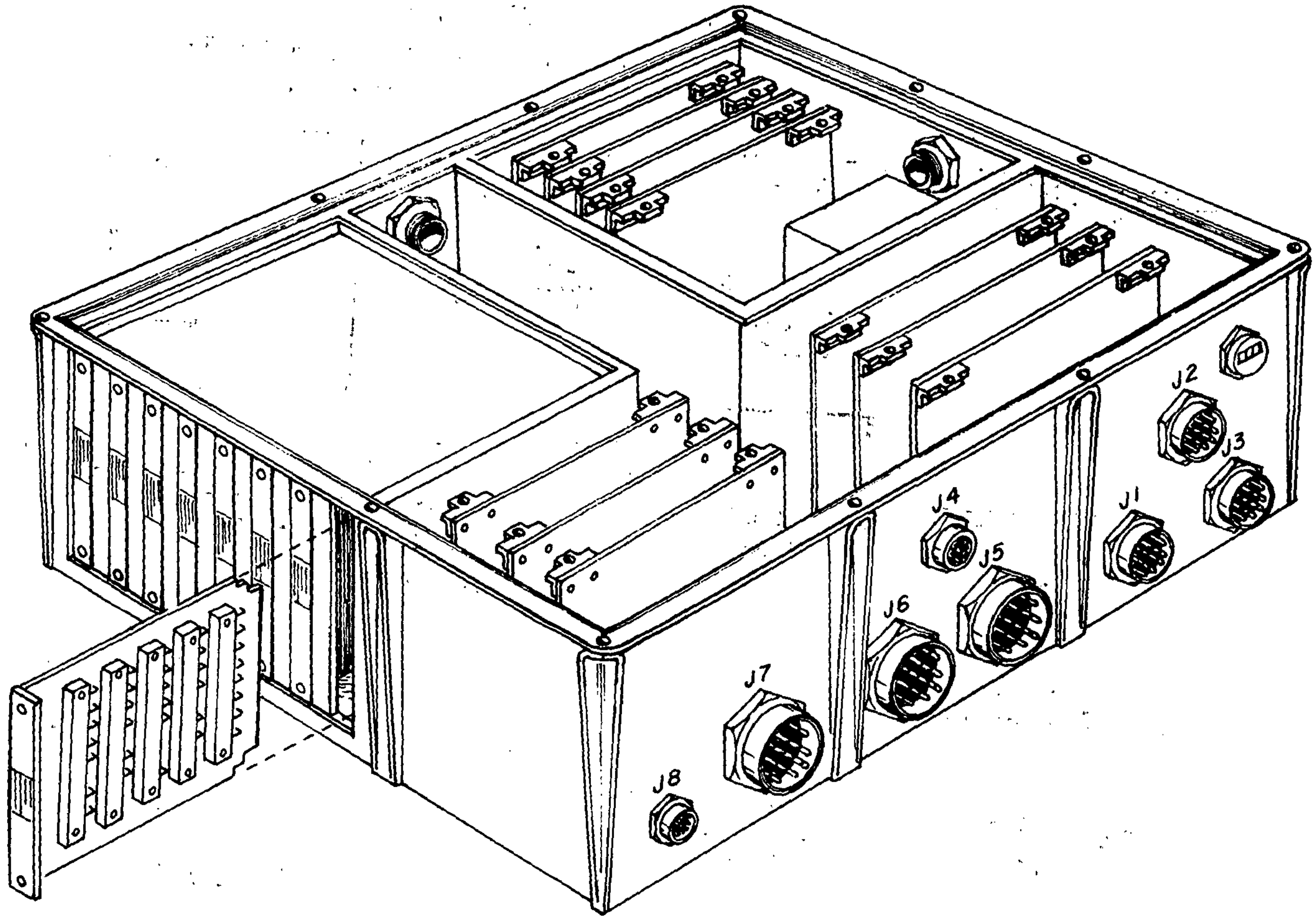

Figure 2. STE Assembly.

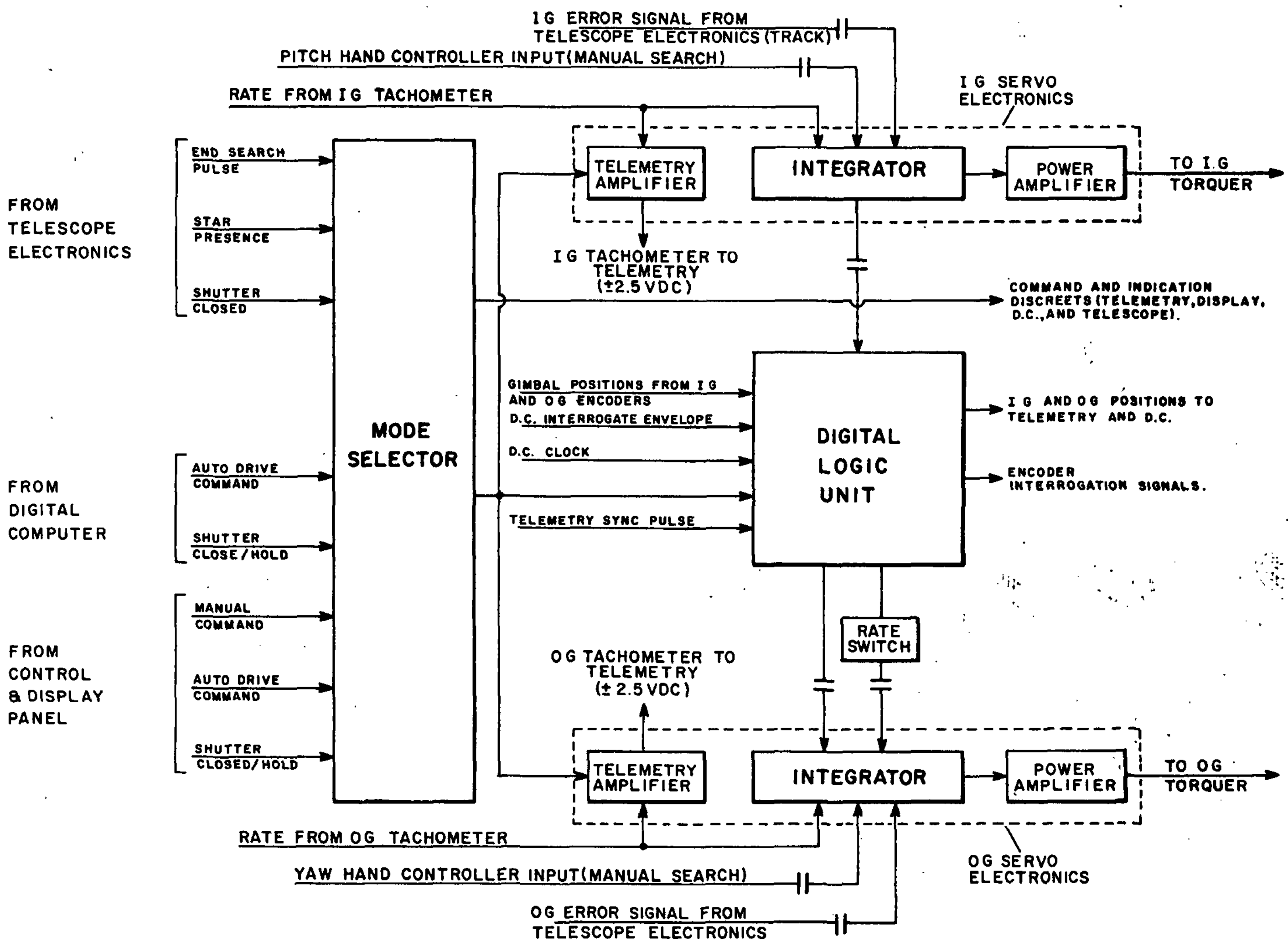

Figure 3. Star tracker functional block diagram.

Modes of operation: Manual (from hand controller), automatic, or shutter close/ hold.

Tracker Specifications

Target star: Canopus (primarily), Achernar, or Alpha Crux. Threshold set at half-magnitude below Alpha Crux.

Tracker field-of-view: Acquisition = 1.7×10^{-2} rad $\pm 23.2 \times 10^{-4}$ rad with Achernar as the star; track = 29×10^{-4} rad.

Tracker accuracy: While tracking at maximum rate of 1.4×10^{-2} rad/s, the maximum error is $\pm 2.9 \times 10^{-4}$ rad.

Tracker limits to earth and sun: To within 8.7×10^{-2} rad of earth; to within 0.78 rad of sun.

Search angles:

	Coarse	Fine
Outer gimbal	0.26 rad ($\pm 29 \times 10^{-4}$ rad)	3.5×10^{-2} rad ($\pm 29 \times 10^{-4}$ rad)
Inner gimbal	$+9.1 \times 10^{-2}$ rad, -7.8×10^{-2} rad, ($+29 \times 10^{-4}$ rad)	$\pm 2.6 \times 10^{-2}$ rad ($\pm 29 \times 10^{-4}$ rad)

Shutter goes from fully open to fully closed in less than one second.

SYSTEM INTERFACE

The star tracker will interface with the ATMDC, the ATM control and display (ATM C&D), the ATM experiment pointing electronics assembly (EPEA), and telemetry. Figure 4 shows the interface block diagram and includes approximate cable lengths. For a complete pin function diagram, refer to Reference 1.

ATMDC

Vehicle roll reference calculations are made in the ATMDC. The star tracker inner and outer gimbal encoder outputs are converted from serial binary to binary coded decimal (BCD). Interrogation and clock pulses are furnished from the ATMDC to the gimbal

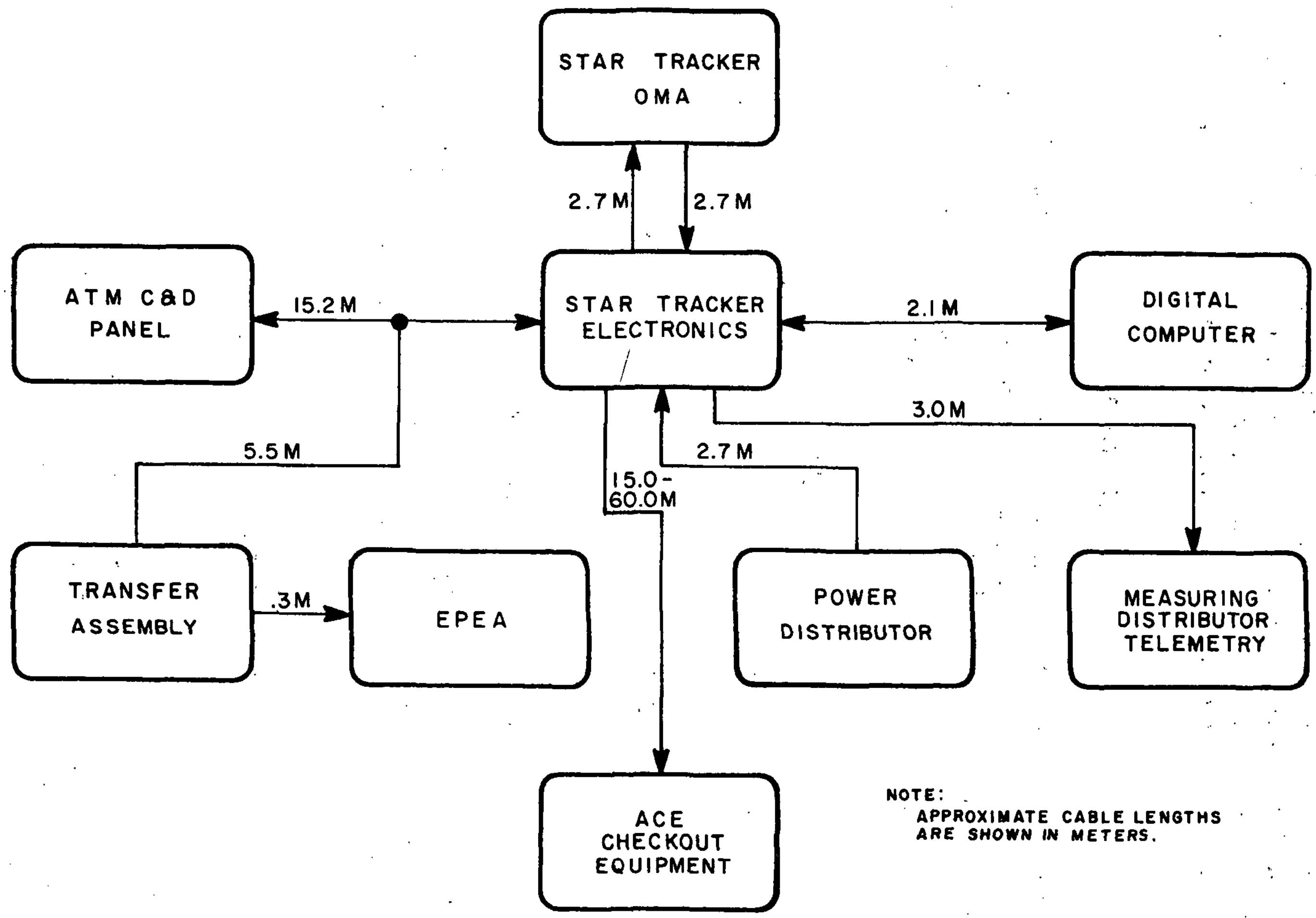

Figure 4. Star tracker interface block diagram.

encoders and the position readout of the encoders is returned. The ATMDC supplies the BCD position data to the ATM C&D where they are displayed in decimal form. A "shutter closed/hold" discrete is furnished from the ATMDC to the tracker when the pointing control system (PCS) modes of operation are reaction control system (RCS) momentum dump, monitor and acquisition, or inertial hold and maneuver. An "auto" discrete is issued to open the shutter and command the tracker to reacquire the reference star.

ATM C&D

The ATM C&D contains switch functions to command automatic, manual, and shutter closed/hold modes. The STE provides discretes to activate flags that indicate star presence, shutter position-gimbal hold, and manual or automatic modes. The tracker system power on-off is also commanded from the control and display panel. The C&D also contains the hand controller to position the gimbals manually.

EPEA

Star tracker manual and automatic commands from the control and display are routed to the EPEA as digital code words. The EPEA issues discretes for these commands to the star tracker control logic. The 800-Hz hand controller drive signals from the C&D are also routed to the EPEA where they were demodulated before transmission to the star tracker servo electronics.

Telemetry

Strobe pulses are transmitted from the telemetry to the star tracker digital logic unit and parallel binary gimbal position data are returned. The output resolution is 145 μrad. Other signals furnished to telemetry will be star presence and shutter-closed indications.

OPERATIONAL CHARACTERISTICS

ATM star tracker modes of operation are automatic, manual, and shutter close/hold. The automatic mode allows the tracker to search for, acquire, and track the reference star. Manually, the gimbals are positioned by the astronaut from the hand controller on the control and display. The shutter close/hold command is initiated manually by the astronaut from the control and display, automatically from the ATMDC, or automatically from the earth albedo and sun sensors. Tables 1 and 2 list the star tracker commands, indications, and operational contingencies.

Automatic Mode

The inner gimbal (IG) and outer gimbal (OG) may be commanded and controlled automatically. A specific field is searched from a given reference point until the target star is acquired. Discrete commands are accepted in the STE from the ATM C&D or ATMDC to activate the search circuits. Drive signals are generated in the STE which position the IG and OG with the servo electronics and gimbal torquers. The search command is received from the mode selector, and the digital logic unit (DLU) electronics cause the gimbals to perform a raster scan.

A two-axis search is conducted in two modes: a fine mode in which a 0.07 × 0.07 rad area centered about the starting position is searched, followed by a coarse mode in which an angle of 0.52 rad about the OG and 0.174 rad about the IG starting positions is searched. If the star is not found when the coarse search is ended, the IG is returned to its initial position, and the coarse search pattern is repeated. The fine mode is not repeated.

The search pattern is characterized by a series of 0.07 rad or 0.52 rad sweeps along the OG with each sweep being separated by 0.013 rad of IG motion. Since the acquisition field-of-view of the telescope is 0.017 rad, the star will not be missed if it is in the search area. The OG is driven by a 0.017 rad/s command applied directly to its rate loop, with the gimbal encoder being used to determine when the proper angle (0.07 or 0.52 rad) has been reached. The IG is indexed the required 0.013 rad by means of its position loop.

If Canopus, Achernar, or Alpha Crux is not acquired, a manual input is required for repositioning, and the search operation is repeated. When the target star is acquired, the search electronics drive signals are disabled and the system goes into a track mode. The IG and OG are then controlled with error signals from the telescope electronics. The STE generates signals for the ATM C&D flags to indicate "STR" and "ACT" when the reference star is acquired and the system is tracking (Table 1).

Manual Mode

Two-axis inputs from the hand controller on the ATM C&D by the astronauts will manually command any desired position of the star tracker gimbals. Drive signals received from the hand controller (via the EPEA) are applied to the gimbal servo electronics to orient the telescope to any desired position within the gimbal limits.

Manual operations are normally required when initially acquiring the target star. The gimbals are positioned within the search limits (OG $\pm$ 0.26 rad, IG + 9.1×10^{-2}, and - 7.8×10^{-2} rad) of the target star and then an automatic command is given. A manual operation is also necessary when it is required to reorient the telescope pointing direction to track an alternate target star. The flags on the ATM C&D will indicate "MAN" and "OPN" for a manual operation with the shutter open (Table 1).

TABLE 1. STAR TRACKER COMMANDS AND INDICATIONS

Command	Resulting Action	ATM C&D Panel Flags[a,b] Acq.	Shutter
Star Tracker "Off" (C&D Panel)	+28 Vdc "Off," Shutter closed.	▨	OPN
Star Tracker "On" (C&D Panel)	+28 Vdc "On," Shutter closed, gimbal hold "On."	▨	▨
Man. (C&D Panel)	Shutter opens, gimbal hold "Off," man. servo-loop "On," precedence over last command. Digital computer cannot override command.	MAN	OPN
Auto (C&D Panel)	Search routine "On," precedence over last command.	ACT	OPN
Auto (C&D Panel) After Star Is Acquired	Search routine "Off," tracking servoloop "On." Tracker locks onto star	ACT	STR
Close/Gimbal Hold (C&D Panel)	Shutter closes, gimbal hold "On," precedence over last command. Digital computer cannot override command.	▨	▨
Close/Gimbal Hold (Digital Computer)	Shutter closes, gimbal hold "On," will not override man. (C&D Panel).	▨	▨
"On" Signal From Earth Albedo Sensor or Sun Sensor	Shutter closes, gimbal hold "On" if last command was auto (digital computer or C&D panel) and star was acquired.	▨	▨
	Shutter closes, gimbal hold "Off" if 1. Last command was auto (digital computer or C&D panel) and star was not acquired.	ACT	▨
	2. Last command was man. (C&D panel).	MAN	▨
"Off" Signal From Earth Albedo Sensor Or Sun Sensor	Shutter opens, tracker switches to mode last commanded. However, if last command was close/gimbal hold (C&D panel or digital computer), shutter will not open.		
Auto (Digital Computer)	Same action as auto (C&D panel), but cannot override man. (C&D panel), or close/gimbal hold (C&D panel).	ACT	OPN

a. Power "Off" flag indications do not necessarily indicate state of star tracker modes.

b. Flag legend:

Acq.		Shutter	
ACT	Searching or Tracking	▨	Shutter Closed
▨	Hold	OPN	Shutter Open
MAN	Manual	STR	Star Presence

TABLE 2. ATM STAR TRACKER OPERATIONAL CONTINGENCIES

Condition	Operation and Mode	Reactions and Required Corrective Actions
Loss Of Target Star Due To An Obstruction	"Auto" tracking target star	C&D panel flags will indicate "ACT" and "OPN." Star tracker gimbals will search (IG $+9.1 \times 10^{-2}$, -7.8×10^{-2} rad and OG $\pm$ 0.26 rad) until target star is reacquired. If target is not found in the search pattern, a manual operation will be required to place tracker in another search area.
Target Star Not Found Within Search Pattern	"Auto" automatic search mode	Star tracker gimbals will continue search pattern (IG $+9.1 \times 10^{-2}$, -7.8×10^{-2} rad and OG $\pm$ 0.26 rad) until a manual operation is initiated. Search area should be relocated and an "auto" command reactivated until target star is acquired.
Target Star Located Near Gimbal Stops	"Auto" automatic search mode	Star tracker gimbals will search a restricted pattern, reversing directions at the gimbal stops. Corrective action not required.
Required Relocation Of Pointing Direction To An Alternate Target Star	"Auto" tracking target star	Star tracker is placed in manual operation and pointed to new target area. It is then commanded into "auto" operation.
Required Verification Of Target Star	"Auto" tracking target star	Tracker is placed in manual operation, target star is verified by previous computer stored routine requiring astronaut to place pointing direction to several other stars in the area. (Trial and error identification method).

Shutter Close/Hold Mode

During specific PCS operational modes or when the target star is occulted by the earth or a vehicle obstruction, it is desirable to maintain the tracker position fixed until reacquisition of the star or other superseding commands are given. A "shutter close/hold" command from the ATM C&D, ATMDC, or the earth albedo sun sensor will activate the logic circuits to hold the gimbals and close the shutter. If the system is in an automatic search mode or a manual mode, the shutter will be closed without the gimbals being held. This will allow the search to continue or allow for continuous manual control. The flags on the C&D will indicate "ACT" for acquisition and the shutter closed (Table 1).

ELECTRONIC CIRCUITS AND CONTROLS

The electronics system is composed of the mode control logic, DLU, telescope electronics, and the servo electronics. The control logic provides for the proper mode to be executed from all the possible input stations; the DLU is a complex digital system that controls all operational modes; the telescope electronics contain all circuitry associated with the photomultiplier tube operations; and the servo electronics provide the controls for the inner and outer gimbals.

Mode Control Logic

Operational Description. The astronaut controls on the control and display panel (manual, shutter close/hold, and auto) will take precedence over the controls from the digital computer (auto and shutter close/hold). The digital computer commands will be effective only after the astronaut has issued an "auto" command.

A mode control logic diagram is shown in Figure 5. The flip-flops (F/F) are gated to satisfy any input commands given in any sequence from any of the command stations.

The two flip-flops W and V are used for the three output modes. The following state assignments are made:

	F/F V	F/F W	MODE
State	"0"	"0"	Hold
	"0"	"1"	Manual
	"1"	"0"	Auto

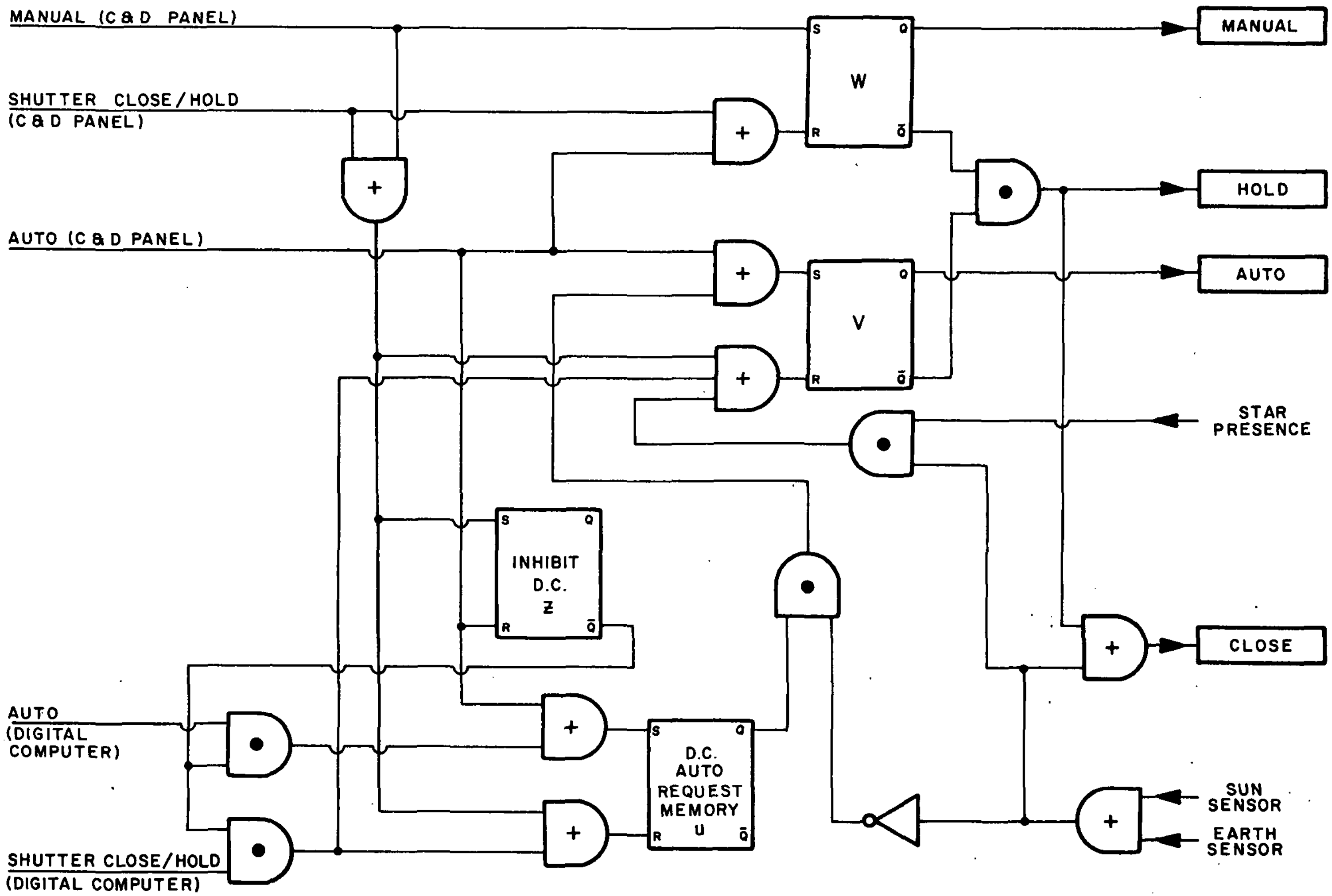

Figure 5. ATM star tracker control logic diagram.

The F/F labeled "Z" is to inhibit the digital computer after a C&D command of "MAN" or "shutter close/hold." The F/F labeled "U" is the "auto request memory" required for the case in which the sun sensor or earth albedo sensor has closed the shutter during a digital computer "HOLD." The sensors will maintain the "HOLD" after the digital computer has commanded "AUTO." If the sensor signal is removed, the tracker will then go into the "AUTO" mode.

Logic Equations. Equations controlling the states of the F/F's may be developed using the following symbols:

Symbol	Input Command	Source
A	Manual	Control and display
B	Auto	Control and display
C	Auto	Digital computer
D	Shutter close/hold	Digital computer
E	Shutter close/hold	Control and display
F	Earth sensor on	Star tracker
G	Sun sensor on	Star tracker
H	Star presence on	Star tracker

The output equations for the F/F's are:

$$W_s = A \quad , \tag{1}$$

$$W_r = B + E \quad , \tag{2}$$

$$Z_s = A + E \quad , \tag{3}$$

$$Z_r = B \quad , \tag{4}$$

and

$$U_s = B + C \cdot Z_r \quad ; \tag{5}$$

or

$$U_s = B + C \cdot B_{t-1} \tag{6}$$

and

$$U_r = A + E + D \cdot Z_r \quad ; \tag{7}$$

or

$$U_r = A + E + D \cdot B_{t-1} \tag{8}$$

and

$$V_s = B + U_s \cdot \bar{F} \cdot \bar{G} \quad ; \tag{9}$$

or

$$V_s = B + \bar{F} \cdot \bar{G} \left(B_{t-1} + C_{t'1} \cdot B_{t'2} \right) \tag{10}$$

and

$$V_r = A + E + Z_r \cdot D + H \cdot (F + G)\, B_{t-1} \quad ; \tag{11}$$

or

$$V_r = A + E + B_{t-1} \; [D + H\,(F + G)] \quad . \tag{12}$$

Digital Logic Unit (DLU)

Functions. The functions of the DLU (Fig. 6) may be divided roughly into two categories; passive and active. The passive functions involve processing the star tracker gimbal position information and delivering it on command to the ATMDC, to telemetry, and to the ATM C&D. The active functions are (1) to control the star tracker telescope gimbal search pattern during automatic search mode and (2) to maintain the gimbals at the angles existing upon receipt of a hold command from the mode control logic.

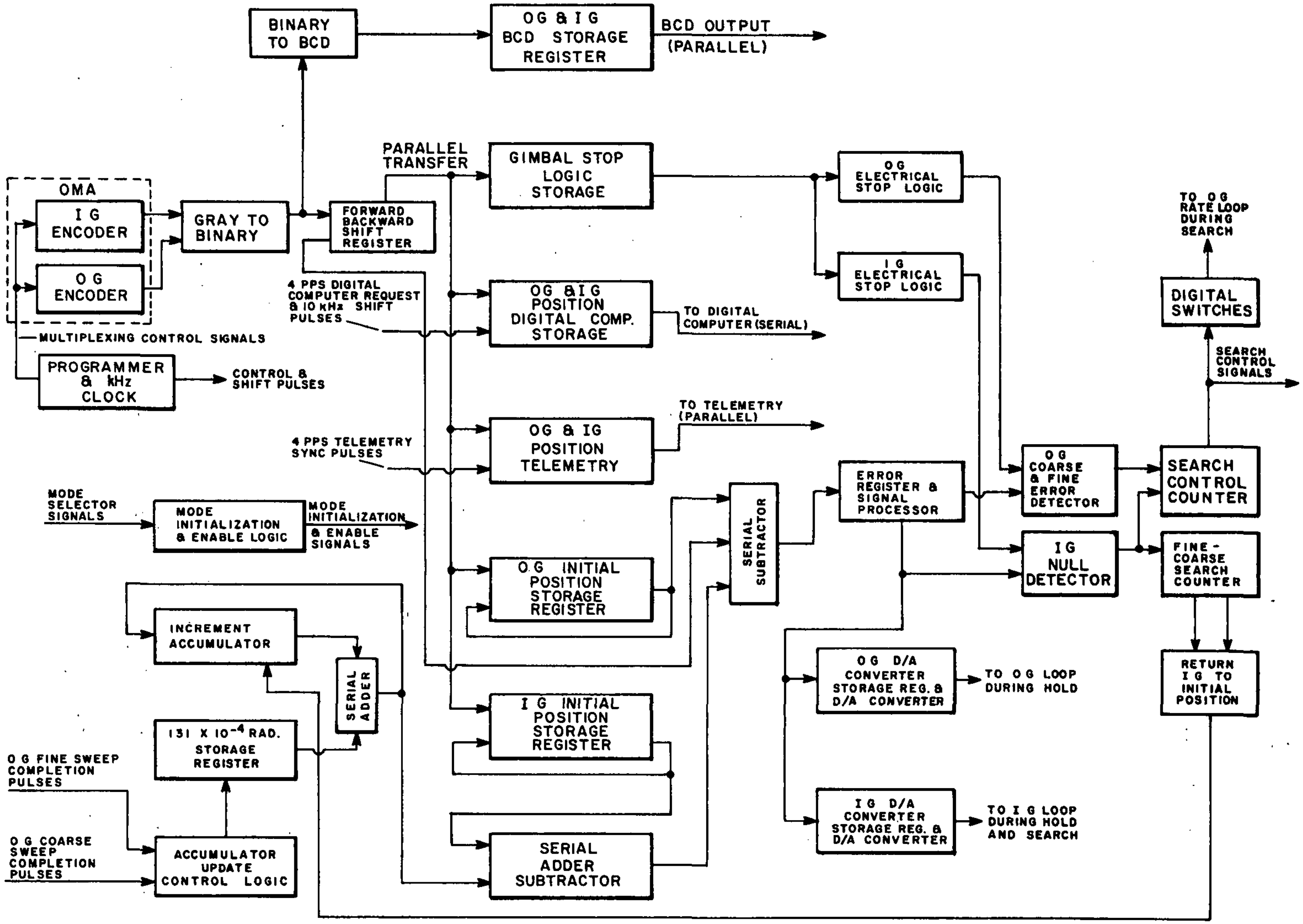

Figure 6. Block diagram of digital logic unit.

Description and Operations. The programmer portion of the DLU contains the 10 kHz clock and generates the multiplexing control and shift pulses. The gray to binary converter, binary to BCD converter, forward-backward shift register, serial subtractor, and error register and signal processor are shared operationally (multiplexed) for both IG and OG operation.

The encoders receive interrogate prepare pulses and 15 clock pulses from the programmer. The encoder gimbal angle, in gray code, most significant bit (MSB) first, is gated into the serial gray to binary (G/B) converter. THe G/B converter output is gated into the forward-backward shift register and, also, into the binary to BCD converter. This converter contains combinational logic such that the conversion takes place as the binary word is shifted in. At the completion of each update and conversion, the BCD word is shifted in parallel into the appropriate IG or OG BCD storage register. The BCD output is used in testing only.

The forward-backward shift register operates in the forward direction when accepting the encoder angle (MSB) first from the G/B converter and in the backward direction for shifting this angle, least significant bit (LSB) first, into the serial subtractor for error determination in the hold mode.

The OG and IG position registers are updated upon the receipt of an interrogate pulse from the ATMDC. Then, the information is shifted out serially to the ATMDC, MSB first, in response to clock pulses from the ATMDC.

The OG and IG telemetry registers are updated, in parallel, from the forward-backward shift registers, upon receipt of a sync pulse from telemetry.

Initial position angles are stored in the IG and OG initial position registers upon receipt of a hold command and at the beginning of the search mode.

In the search mode, the IG starts at the initial position and moves in positive and negative multiples of 131×10^{-4} rad, alternately, at the completion of each OG sweep. This is accomplished by adding 131×10^{-4} rad from a storage register to the contents of the increment accumulator, and alternately adding and subtracting this sum to the contents of the IG initial position register. The IG position word, from the forward-backward shift register, is subtracted from that resulting sum, with the difference registered in the error register and signal processor, and then shifted to the IG digital-to-analog (D/A) converter storage register. The error is converted to a dc voltage which is routed to the IG position loop electronics. The OG sweeps alternately plus and minus as determined by the OG coarse and fine error detector, search control counter, and IG null detector. Digital switches are used to provide the required positive or negative dc voltage to the OG rate loop electronics. The fine-coarse search counter returns the IG to the initial position at the completion of the fine search pattern and then at the completion of the coarse search pattern.

In the hold mode, the OG and IG positions are subtracted from the contents of the OG and IG initial position registers, as determined by the multiplexing control signals. The errors are transferred to the appropriate registers and D/A converters which provide dc error signals to the position control loops.

Telescope Electronics

Inputs-Outputs. The following discussion of the telescope electronics is not intended as an analytical discussion, but as a functional description of the principles used. Frequent reference to Figure 7 will clarify terminology and relation of the modules discussed.

The inputs to the telescope and electronics are:

1. Signals from starlight, sun, earth, and reflected light to protection sensors

2. Power ±12 Vdc, +28 Vdc, and +5 Vdc.

The outputs are:

1. Two 2.8 mV/4.85 μrad dc signals for $\pm$ 104 $\times$ 10^{-4} rad

2. Star presence indication

3. Tracking indication

4. Shutter-closed and shutter-open indication.

Functions and Operational Descriptions. The function of the telescope electronics includes a set of two-axis error signals, star presence indication, and protection of the photosensitive element from intense light of the sun or earth. This electronics is packaged in two separate assemblies (HVPS and telescope electronics assembly) mounted on the IG telescope assembly. The HVPS provides the potentials for focusing, accelerating, and current multiplying of the electron beam generated by the photocathode. It also provides a 3200-Hz reference signal. The combination of the optics, photocathode, high voltage power supply, dynodes, and anode provides a dc current of 150 nA, nonresolved signal with a field-of-view of 29.09 $\times$ 10^{-4} rad. The telescope electronics assembly contains the remaining telescope electronics that amplify and resolve the anode current to a two-axis error signal of 2.8 mV/4.85 μrad and extends the field-of-view to 175 $\times$ 10^{-4} rad. This box also contains the electronics to control the shutter for protecting the optics and the photocathode from intense light and contamination.

Around the photomultiplier tube are two sets of two-axis deflection coils which generate magnetic fields. These fields deflect the electron beam from the photocathode in

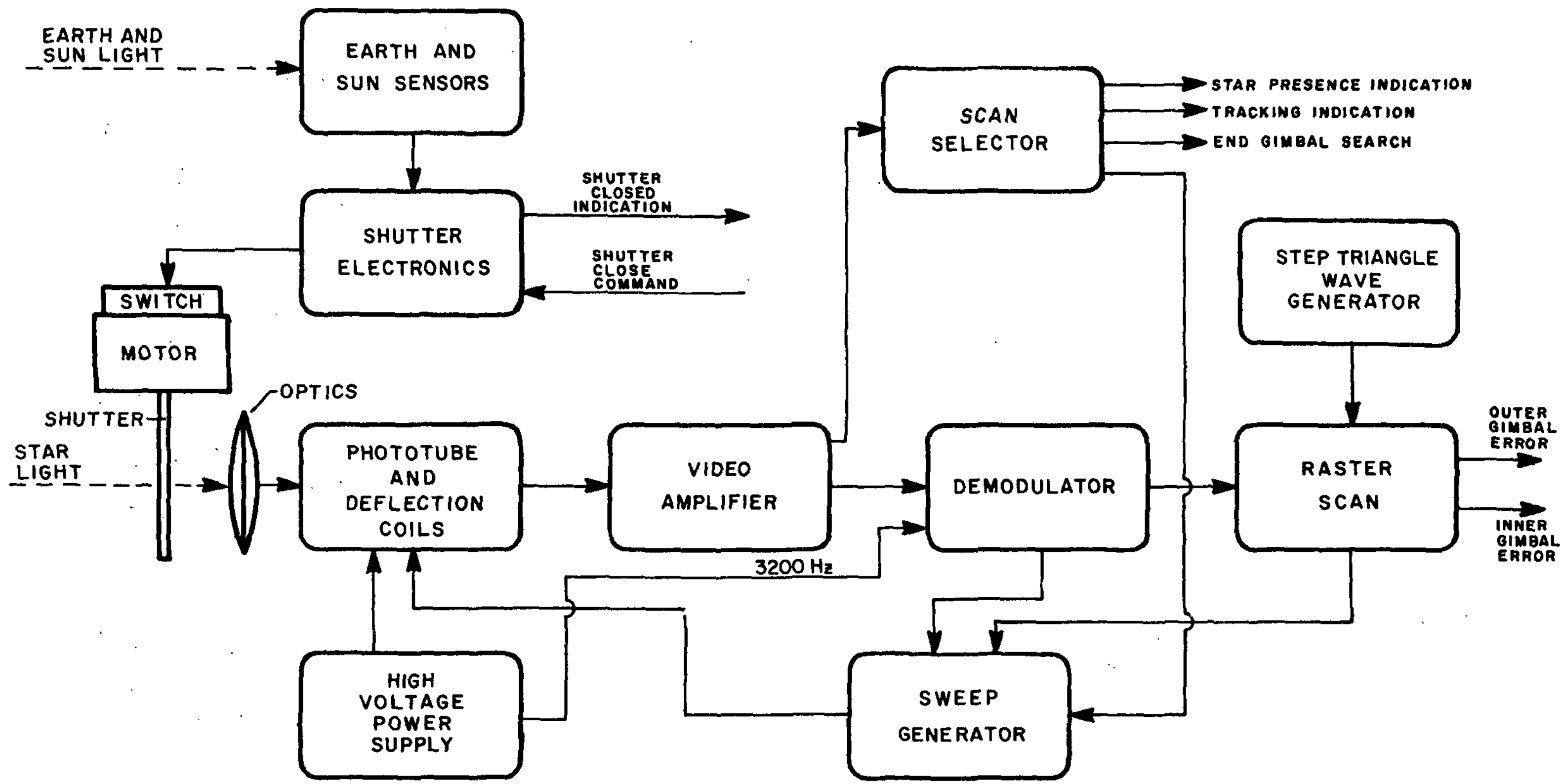

Figure 7. Star tracker telescope electronics block diagram.

time-varying sequence on each axis such that an electron beam from any point on the photocathode can be deflected in the aperture and generate an "On" anode current. The time of the "On" current compared to field timing (i.e., coil current) contains the error information.

The sweep pattern chosen largely determines the electronics requirements for search, acquisition, sweep, and demodulation. The tracker uses a raster scan which requires a 25-Hz, stepped triangle wave and a 200-Hz triangle wave. After star acquisition, the second set of coils shares an 800-Hz triangle current source gated with 400 Hz that produces a cross pattern or cruciform.

A reference frequency for the sweep and gating signals is provided by the high voltage power supply, approximately 3200 Hz. A binary countdown provides 1600 Hz, 800 Hz, and 400 Hz, and each is inverted. This is located in the demodulator card. A 400-Hz reference is fed to the stepped triangle wave generator where a 25-Hz, 16-step triangle wave and a 200-Hz triangle wave are produced.

These two waveforms are fed through analog gates (control of gates will be discussed later) and into two separate true current amplifiers. The output waves are fed into the vertical and horizontal dc deflection coils. Magnetic fields generated by these current waveforms search the photocathode for an electron beam generated by starlight focused on the element. If a light enters the 175×10^{-4} rad field-of-view, an "On" current enters the 29.09×10^{-4} rad aperture and is multiplied by the dynodes secondary emission with a gain of 10^6 in the form of a pulse current approximately 0.35 ms wide, 150 nA negative (starlight dependent). A series of pulses results at 50-Hz rate (2 pulses per half of stepped triangle wave).

<u>Sequence Description.</u> From this point, a sequence description is used to explain the operation of the telescope electronics. In the video amplifier, anode current pulses are amplified and conditioned to provide triggering pulses for the scan selector and demodulation input. A threshold detector provides a dc level output if repetitive pulses are received within a specified time. This level provides a star presence indication. A second output from the video amplifier provides a pulse to the scan selector. The processed video output is a +5 V level and is clamped to 0 V when a pulse is received for the input to the demodulator. A gain adjustment in the video amplifier determines a minimum star magnitude for tracking.

The scan selector accepts the dc level and pulses from the video amplifier and provides a star presence indication, scan selection (raster or cruciform), end gimbal search signal, and tracking indication. The input pulse is accepted by a level detector. A four-input NAND gate allows the gate to inhibit the pulse from the level detector. A monostable provides a 100-ms delay so that the gimbal mechanical search will continue in the direction it was moving at the first acquisition and disregard a random input during search. After the 100-ms delay, a gimbal search stop signal is provided and a second 100-ms monostable is triggered. This allows transient settling in the gimbals.

At the instant the scan selector switches from raster scan to cruciform, the raster scan has coil currents that are proportional to the position within the 175×10^{-4} rad field. An RC time constant in the dc coil constant current source provides a sample hold feature until the instantaneous field is deflected to that position.

The sweep generator output is enabled in the cruciform coils. The sweep generator contains an 800-Hz triangle current wave that is gated between the vertical and horizontal coils by 400 Hz. The resulting beam deflection is a dc or constant deflection and a cross pattern. When the sweep generator is enabled, the output of the video amplifier becomes a pulse width modulated +5 V with the off-time determined by the length of time that the cross pattern is inside the instantaneous field-of-view. This pulse width modulated train is a two-way time shared signal.

The pulse width signal is resolved and demodulated in the demodulator. The pulse train gated with 400 Hz and 400 Hz (phase shifted 3.14 rad) resolves the signal into two axes. Each of these gated with 800 Hz and 800 Hz (phase shifted 3.14 rad) shifted by 1.57 rad provides the polarity demodulation. The amplitude is determined by the pulse durations. The two polarity signals are summed by gating a matched plus and minus 9 Vdc to charge an RC network.

The output of the demodulator is fed into the raster scan current amplifier and affects a nulling of the instantaneous field on the star position by providing a dc error signal to the current amplifiers in the raster scan circuit.

At this point the combination of the tube and electronics could be considered a 0.0175 rad field-of-view strapdown star tracker whose error readouts are the currents in the respective dc coil and with an instantaneous field-of-view of 29.09×10^{-4} rad. The primary advantage is the elimination of noise and random light outside the 29.09×10^{-4} rad field. These two resolved dc error signals are an input to the servo rate loop that nulls these error signals to bring the star tracker center line coincident with the star line.

Servo Electronics

Functions and Description. The gimbal servo system consists of a rate-controlled driver which varies the gimbal position and/or rate according to commands from a number of different sources. The two gimbals and their functions are similar, so only one will be described here. Figure 8 is a block diagram of the essential elements of the system.

There are four different modes of operation; hence four inputs to the rate loop electronics (Fig. 8). The power amplifier and summing network constitute the entire electronics and these electronics are compensated to accommodate both the telescope loop and the encoder position loop. The torquer (an Inland Mode 2201) drives the gimbal inertia and friction and produces a rate. This rate is measured by a tachometer (Inland

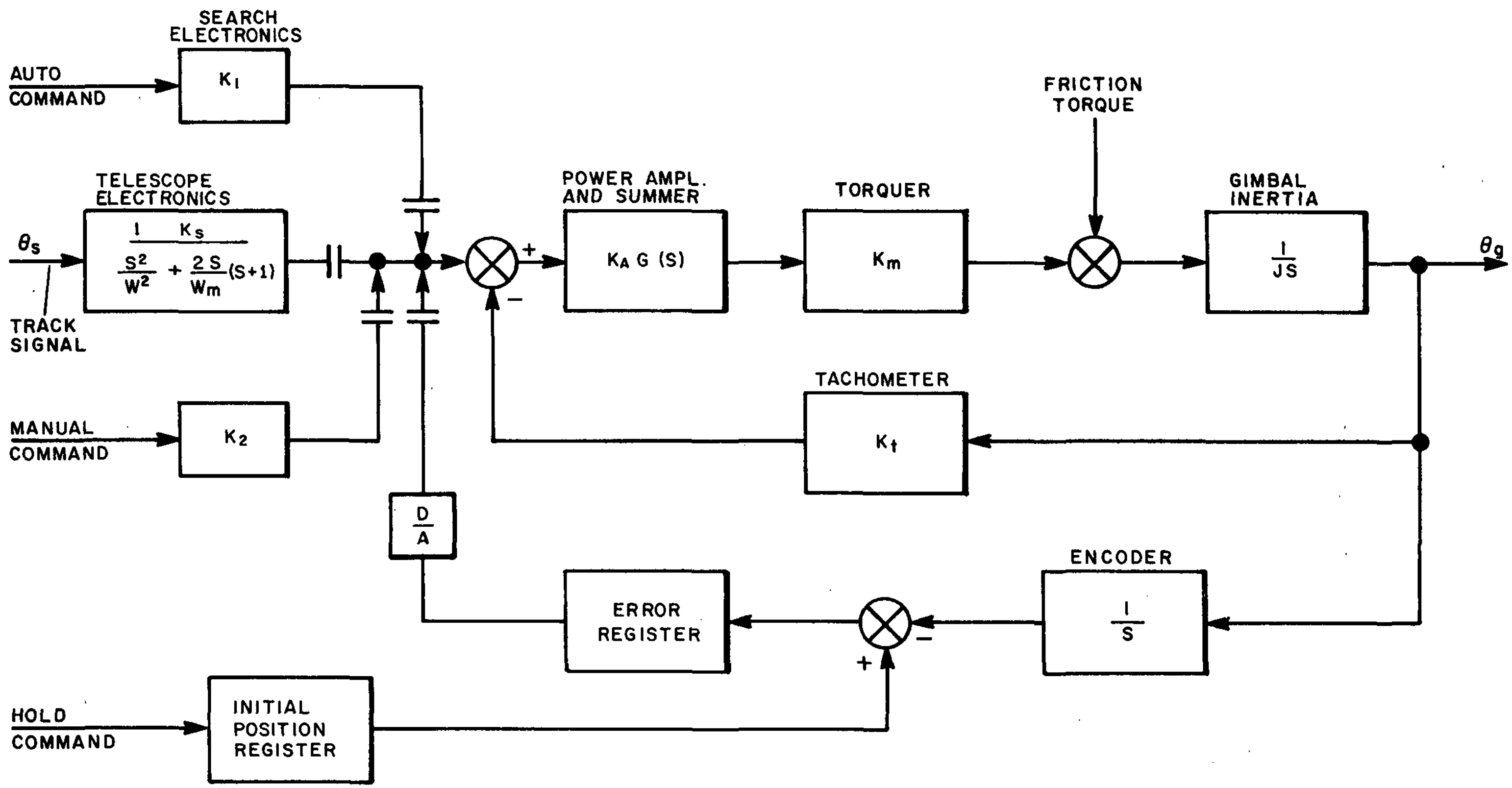

Figure 8. Block diagram of ATM star tracker gimbal servo system.

Model TG 2123) and fed back to force the gimbal to move at a constant rate determined by the command input. This rate is also kinematically integrated to produce position information which is measured by an optical encoder. In the hold mode, the position difference signal will be fed back to become the rate command input and bring this error to zero.

MECHANICAL AND THERMAL DESIGN

The star tracker OMA and electronics assembly have been designed to meet the launch environment as well as to operate within specifications in a space environment. The OMA was designed with structural symmetry and with materials of similar coefficients of expansion. Modular construction has been used in the assembly of the OMA to allow for simultaneous testing and subassembly work.

The STE box is made of aluminum sheet metal with inner walls around the DLU and power supply sections. The design allows conduction of the heat to the top surface, as per the ATM thermal requirements.

Mechanical Description

The star tracker OMA comprises a refractive telescope mounted in a double gimbal suspension. Gimbal freedom is ± 1.51 rad around the outer gimbal axis and ± 0.70 rad around the inner gimbal axis. Major elements in the mechanical assembly consist of the frame, gimbal, inner and outer torquer pivots, inner and outer encoder pivots, and the telescope assembly which also includes the sunshade and shutter.

To afford maximum gimbal rigidity and avoid sliding fit hangup, both bearing pairs in both gimbal pivots are securely preloaded. This requires a close match of material coefficients. To provide a lightweight alloy with a coefficient of expansion matching stainless steel, A-390 aluminum alloy is used for the frame and gimbals. A three-point mount below the center of gravity is located on the frame. The frame pivot bores are line bored accurately with respect to the plane of the mounting feet and also the pad which receives an alignment reference mirror.

The gimbal torquer pivots consist of a housing, shaft, bearings, torque motor, rate tachometer, flex leads, terminal board, and cover. Basically, a pair of 440C, preloaded, angular contact ball bearings accurately pivots the shaft on which the motor and tachometer rotor adapters are mounted. To insure interchangeability, each assembly is constricted such that a close tolerance dimension is held between the locating flanges on the housing and the shaft.

The gimbal encoder pivots consist of essentially the same parts as the torquer pivots, except the torque motor and rate tachometer are replaced by an encoder assembly. This assembly consists of a hub, mounting plate, angular contact bearing pair, coded optical disk, light source, readout array, and a pair of printed circuit component boards. Rotational coupling between the pivot shaft and the encoder disk hub is by means of a metal bellows.

To provide long-term reliable lubrication with the smooth performance required, a system employing a fluorosilicone oil is used.

To permit tracking a guide star within 0.78 rad of the sun line and 8.7×10^{-2} rad of earth reflection, a sunshade is extended beyond the lens along the optical axis. The assembly consists of a machined aluminum tube with black optical baffles. A sun sensor and earth sensor are mounted adjacent to the open entry of the tube. A hinged shutter door provides closure of the tube against contamination and damaging, high-intensity stray light. The shutter is spring loaded to open and a steel tape is wrapped around a drum to return the door to a closed position as required. Pull-force is exerted on the tape by means of a jackscrew and nut driven by a dc torquer motor.

Thermal Design and Requirements

Sink temperatures of the star tracker OMA have been calculated to be -84.4°C nonoperating and -56.7°C operating. The OMA design has considered these environmental conditions as well as the temperature limits of the components. The operating and storage temperature extremes are shown in Table 3.

Heaters have been provided on the OMA to maintain a minimum temperature of -18°C. The heaters are located as follows: telescope housing, 10 W; gimbal-mounted encoder, 10 W; and frame-mounted encoder, 10 W. Twin power resistors are located on the encoder pivots and a tube type heater in the telescope housing. Disk type thermostat switches directly control the heaters and are arranged in a series-parallel circuit for more reliability.

Inner and outer gimbal encoder covers will be insulated with a fiberglass liner and multilayer aluminized mylar sandwich. The outer frame will be provided with a lower cover to reduce heat rejection toward the vehicle rack. This cover will be formed of heat treated, 0.031 aluminum alloy, the OMA side being fitted with an aluminized multilayer mylar blanket. The lower side will be painted with pyromark white paint. Fiberglass spacers will be used at points of attachment to the frame flange. The inside surfaces of the OMA are painted with cat-a-lac epoxy black paint. Surfaces external are painted with pyromark white. The STE is painted with cat-a-lac black also.

An adiabatic interface is to be provided between the OMA mounting bracket and the rack structure. The mounting bracket will be insulated with the OMA frame to maintain

TABLE 3. STAR TRACKER TEMPERATURE EXTREMES

System Temperature Extremes (°C)				
	Operating		Storage	
	High	Low	High	Low
OMA Sink (Approximate)	+10	-57	+38	-84
Case	+32	-18	+55	-18
STE Components	+75	-6	+100	-56
Case	+55	-26	+70	-50
STE Sink (Approximate) (Allowable)	+37	-81	+100	-56

Component Temperature Extremes (°C)				
ATM Component	Operating		Storage	
	High	Low	High	Low
Encoders	+55	-26	+85	-65
Phototube	+55	-18	+55	-18
Sensors (Sun and Earth)	+35	-97	+55	-100
Torque Motor	+75	-56	+100	-56
Shutter Motor	+75	-56	+100	-56
Sunshade	+100	-97	+100	-97
Lens	+55	-65	+71	-65
Star Tracker Electronics	+75	-26	+100	-56
Telescope Electronics	+75	-26	+100	-56
Tachometer	+75	-56	+100	-56

the bracket at the same thermal level as the star tracker. The mounting bracket also will be made of stainless steel with a matching coefficient of expansion of A-390 to assure a minimum stress. These design requirements will prevent excessive mechanical stresses in the star tracker gimbals from temperature gradients.

TEST REQUIREMENTS AND GROUND SUPPORT EQUIPMENT

Test Console

A complete set of electrical final checkout test equipment will be provided to MSFC, S&E-ASTR-G by the contractor. The test console will consist of the panels shown in Figure 9. All cables from the OMA and STE will interface with the console for commands, display, and monitoring functions in the laboratory.

Monitor Test Panel

In addition to the laboratory test console, a monitor test and command panel has been designed to functionally test and troubleshoot the star tracker system. This equipment is a "suitcase" design appropriate for "carry-near" test at the vehicle test sights. A functional block diagram of the test panel is shown in Figure 10 and a pictorial view in Figure 11.

Optical-Mechanical Test Station

The optical-mechanical test station contains a star tracker OMA and a star simulator mounted at right angles on dividing heads. The dividing heads are aligned with autocollimators. Both dividing heads have the capability for manual or motor driven positioning to simulate acquisition and tracking operations. The complete test station is housed in a dark room to eliminate stray light interference.

Acceptance Test

The tests that are to be performed on all star tracker systems are listed in Table 4. These tests may be performed in the laboratory using the test console or on the assembled ATM vehicle using the system input-outputs. It should be noted that testing at the Kennedy Space Center (KSC) after the vehicle has been stacked will be restricted because of the test guidelines established and the location of the tracker on the rack. The contractor will perform acceptance tests in accordance with Reference 2.

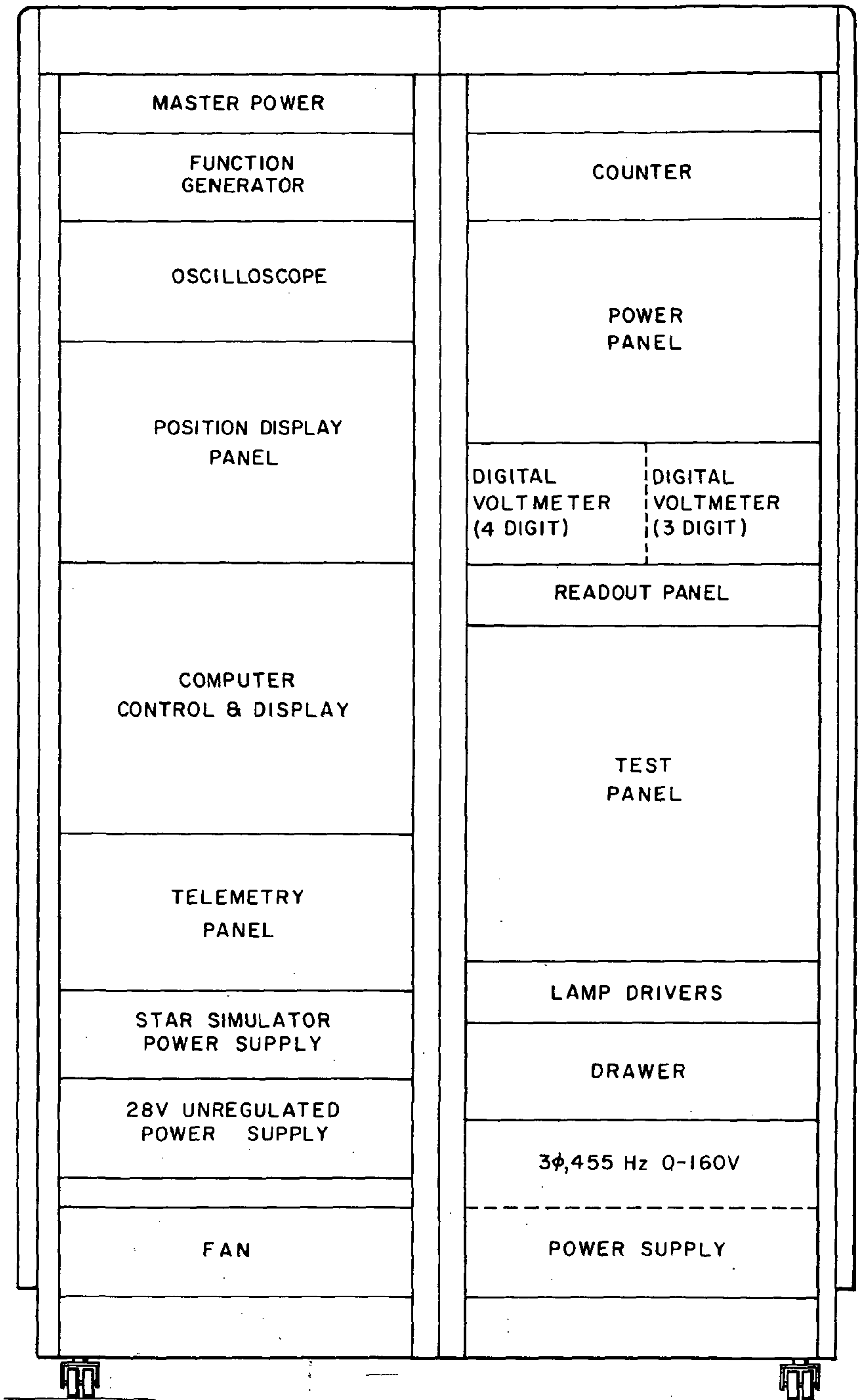

Figure 9. Star tracker test console.

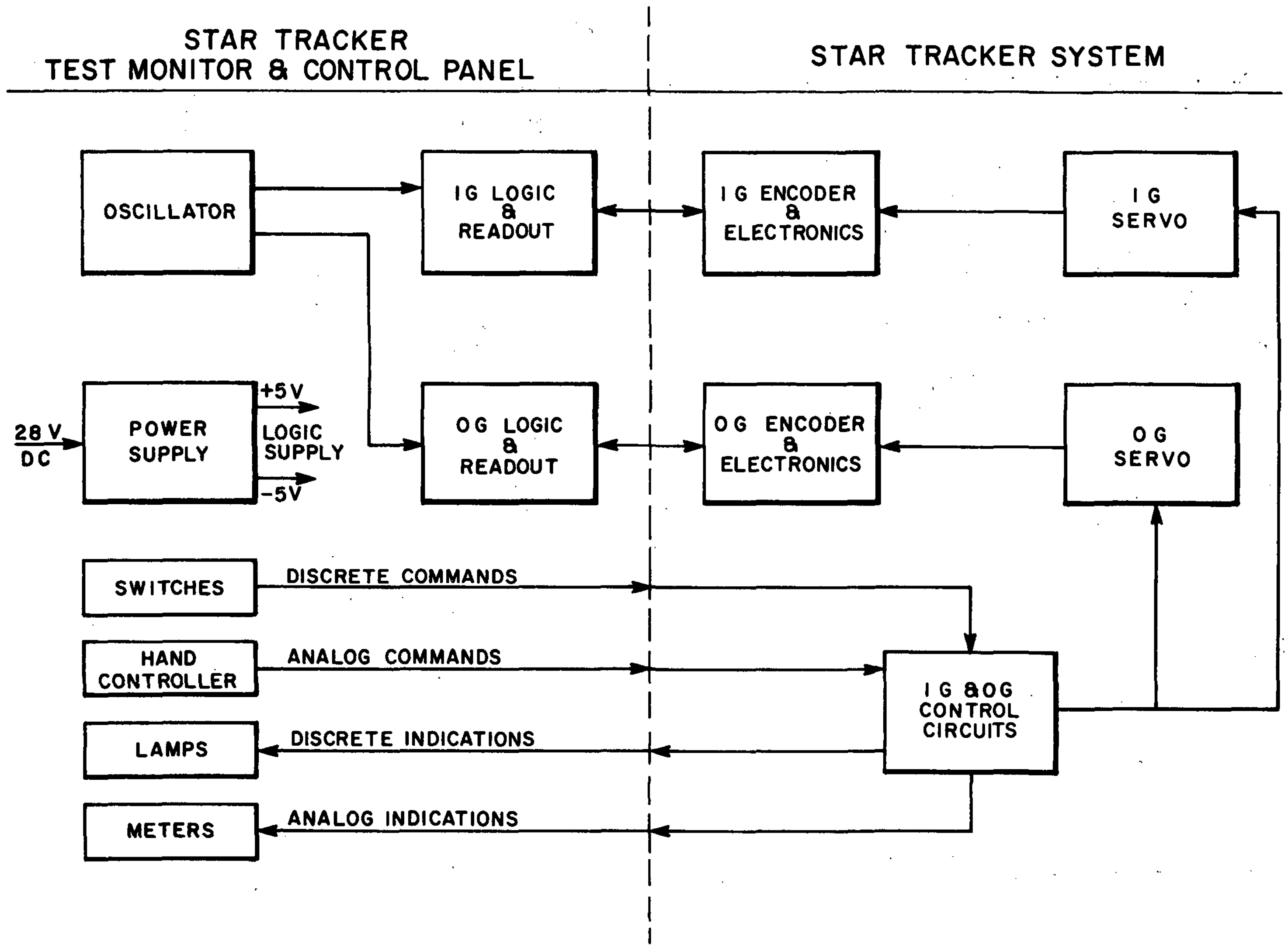

Figure 10. Star tracker test panel functional block diagram.

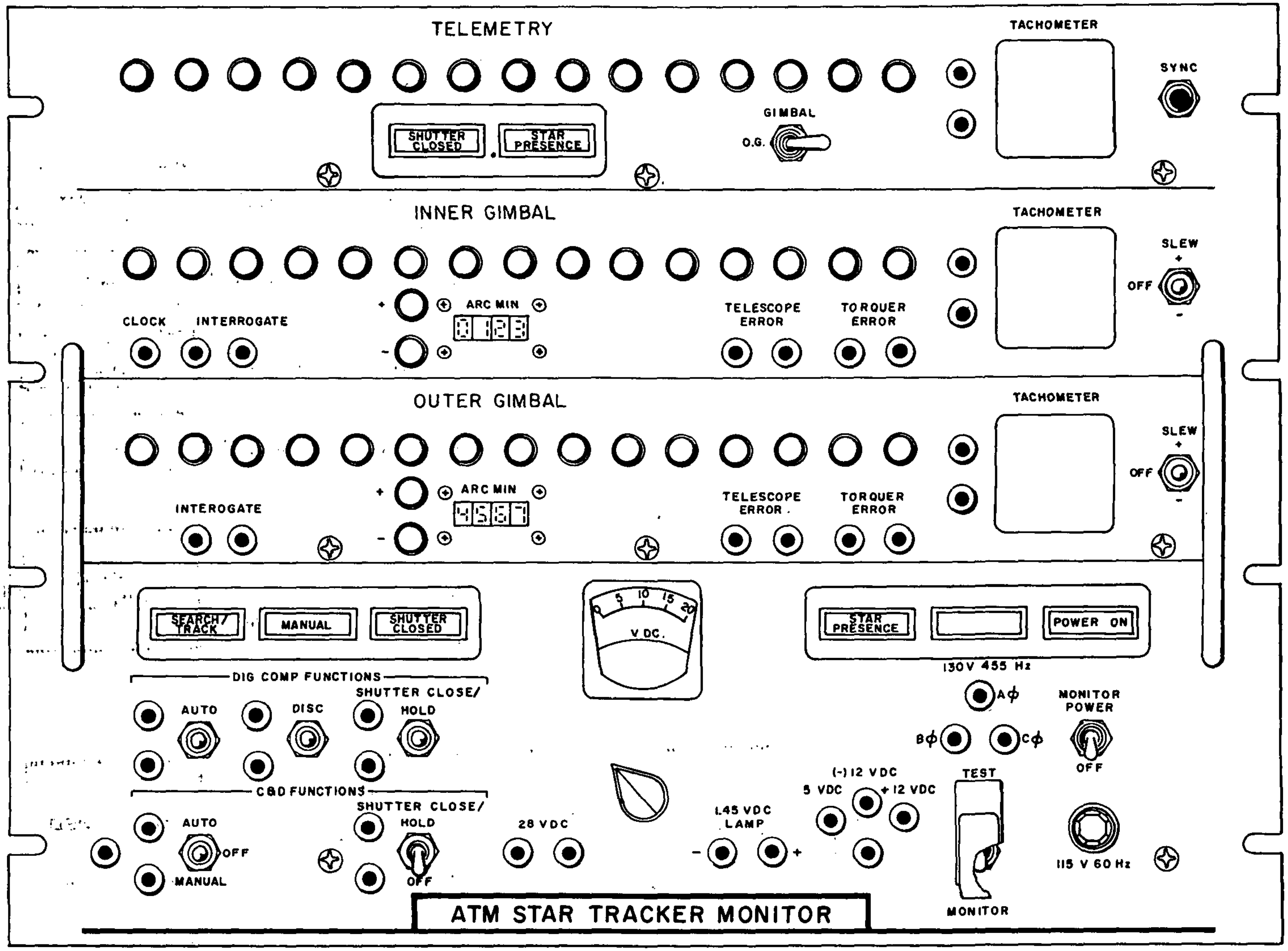

Figure 11. ATM star tracker monitor.

TABLE 4. STAR TRACKER ACCEPTANCE TESTS

Test Requirements	Specifications and Criteria
Power Verification	
Encoder Lamp	1.45 Vdc ± 1%
Logic	5 Vdc ± 5%
Telescope	± 12 Vdc ± 1%
Gimbal Amplifiers	+ 28 Vdc (± 2 V), -28 Vdc (± 2 V)
Input Power	130 V, 455 Hz, 3ϕ
Mode Select	
Manual Mode Auto Mode Shutter Close/Hold Mode	Verify proper C&D panel flag display
Protective Sensor Operation	
Earth Albedo Sensor Sun Sensor	Verify shutter closes/opens When optical axis approaches: 8.7×10^{-2} (+ 5.23×10^{-2}, -0) rad to earth albedo simulator 0.78 (+ 8.7×10^{-2}, -0) rad to sun simulator
Manual Mode	
Hand Controller Operation	Verify: 0 ± 5 Vdc hand controller input 2.5 ± 0.1 Vdc/deg/4.8 μrad tachometer outputs Gimbal readout – angle and proper phasing
System Nulls	
With Star Input With No Star Input	Nominal positions for IG and OG – ± 290 μrad Tachometer output – 0 ± 0.10 Vdc Star presence signal (on/off) – 0 or + 28 (+ 2, - 4) Vdc

TABLE 4. (Concluded)

Test Requirements	Specifications and Criteria
Search Operation	
Verify pattern (fine and coarse) and rates Verify end point and gimbal stop/reversal	Fine search: The tracker should search over a ± 0.262 rad (± 29.09 rad) IG pattern and ± 0.039 rad (± 29.09 rad) OG pattern. Search completion in less than 45 s. Coarse search: After completing fine search, the tracker should search over pattern $+ 9.1 \times 10^{-2}$ rad, $- 7.8 \times 10^{-2}$ rad (± 29.09 rad) IG and ± 15 deg (± 29.09 rad) OG. Search completion in less than 9 min. Verify gimbal limits: OG ± 1.51 ($\pm 87.3 \times 10^{-4}$) rad; IG ± 0.70 ($\pm 87.3 \times 10^{-4}$) rad
Verify Star Acquisition and Tracking for	
Canopus Achernar Alpha Crux	Star acquired within 45 s (initially gimbals to be positioned within $\pm 3.5 \times 10^{-2}$ rad of star) Star presence signal (off/on) 0 or 28 (+ 2, - 4) Vdc Tachometer signal 2.5 ± 0.1 Vdc/ 1.7×10^{-2} rad/s Gimbal positions $\pm 2.9 \times 10^{-4}$ rad NOTE: Star simulator to be moved at nominal 0.87×10^{-2} rad/s
Telemetry Outputs	Verify telemetry channel assignments Digital "0" 0 – 1.5 Vdc "1" 3.5 – 6 Vdc
Digital Computer Interface	
Digital computer commands Verify star tracker to digital computer signals	Verify proper mode interlocks Verify IG and OG positions Digital "0" 0 – 0.5 Vdc "1" 2.4 – 5.5 Vdc

Qualification Test

The first flight star tracker OMA and STE will undergo environmental testing by the contractor in accordance with Reference 3. No deviations are made except the high and low temperature requirements, humidity test, and altitude test.

Acceptance Checkout Equipment (ACE)

Ground support test programs for ATM will utilize the ACE system at MSFC and KSC. All test functions are made available on the STE test plugs; however, signals that are considered sensitive to noise will not be coupled into the ACE system (approximately 60 m cable interface).

OCCULTATION STUDIES

A computer study has been performed to evaluate the vehicle occultation of the star tracker [4]. This study establishes the requirements for the three target stars (Canopus, Achernar, and Alpha Crux). It also considers the worst case mission constraints and reflective zones around the solar arrays. A series of occultation graphs indicate the occultation periods for all the target stars. It was found that 2- to 3-day periods of occultations would be possible, depending upon the launch date and hour.

Additional studies have considered the earth occultation, have generated the requirements for a computer program to determine the most suitable target star, and have provided criteria for star verification.

CONCLUSION

The ATM star tracker is a second generation of a system developed for the Goddard Space Flight Center Orbiting Astronomical Observatory program. However, it has been designed specifically to meet the requirements of the Skylab vehicle and the Skylab mission. Consideration was given to incorporate the state-of-the-art in star trackers without additional research and development. The design has a maximum reliability in a simplex system by providing proven concepts, highly reliable parts, and extensive tests. Laboratory functional tests, environmental qualification tests, and life tests have provided a high confidence factor in the performance of the star tracker in the laboratory and on the Skylab mission.

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3. Environmental Design and Qualification Test Criteria for ATM Components, MSFC Drawing No. 50M02408, Revision D, February 5, 1970 (Original date, January 31, 1967).

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APPROVAL

STAR TRACKER FOR THE APOLLO TELESCOPE MOUNT

By Charles E. Lee

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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