

SECTION XI

AVIONICS SYSTEMS MAINTENANCE

11-1. SCOPE OF SECTION

11-2. This section provides functional and circuit analysis of avionics systems. This section is divided into three separate parts. The first part covers maintenance instructions that include operational checkout, trouble analysis, and removal; the second part covers avionic adjustments; the third part covers adjustments required after the replacement of various critical components.

11-3. DESCRIPTION AND LEADING PARTICULARS

11-4. The avionics systems are the Vehicle Attitude Control system, the Jet Engine Attitude Control system, and the Lunar Simulation system. The Vehicle Attitude Control system consists of primary control, backup control and monitor subsystems. The monitor subsystem provides detection of failures and automatic switching of the control system to a safe mode of operation. The Jet Engine Attitude Control system consists of weight/drag, gimbal hydraulic and jet engine instrumentation subsystems. The Lunar Simulation system consists of drag compensation, thrust/weight control, jet stabilization and autothrottle electronic subsystems. A brief functional analysis is provided for the subsystems included in the three major systems.

11-5. The major equipment included in the avionics systems is the Attitude Control system - Primary Electronics, Attitude Control system Monitor Electronics, Backup Electronics - Rocket Valve Amplifier and Power Supply, Drag Compensation unit (figure 11-1), the Attitude Gyro unit (figure 11-2), two Rate Gyro Triads (figure 11-3), two Accelerometer

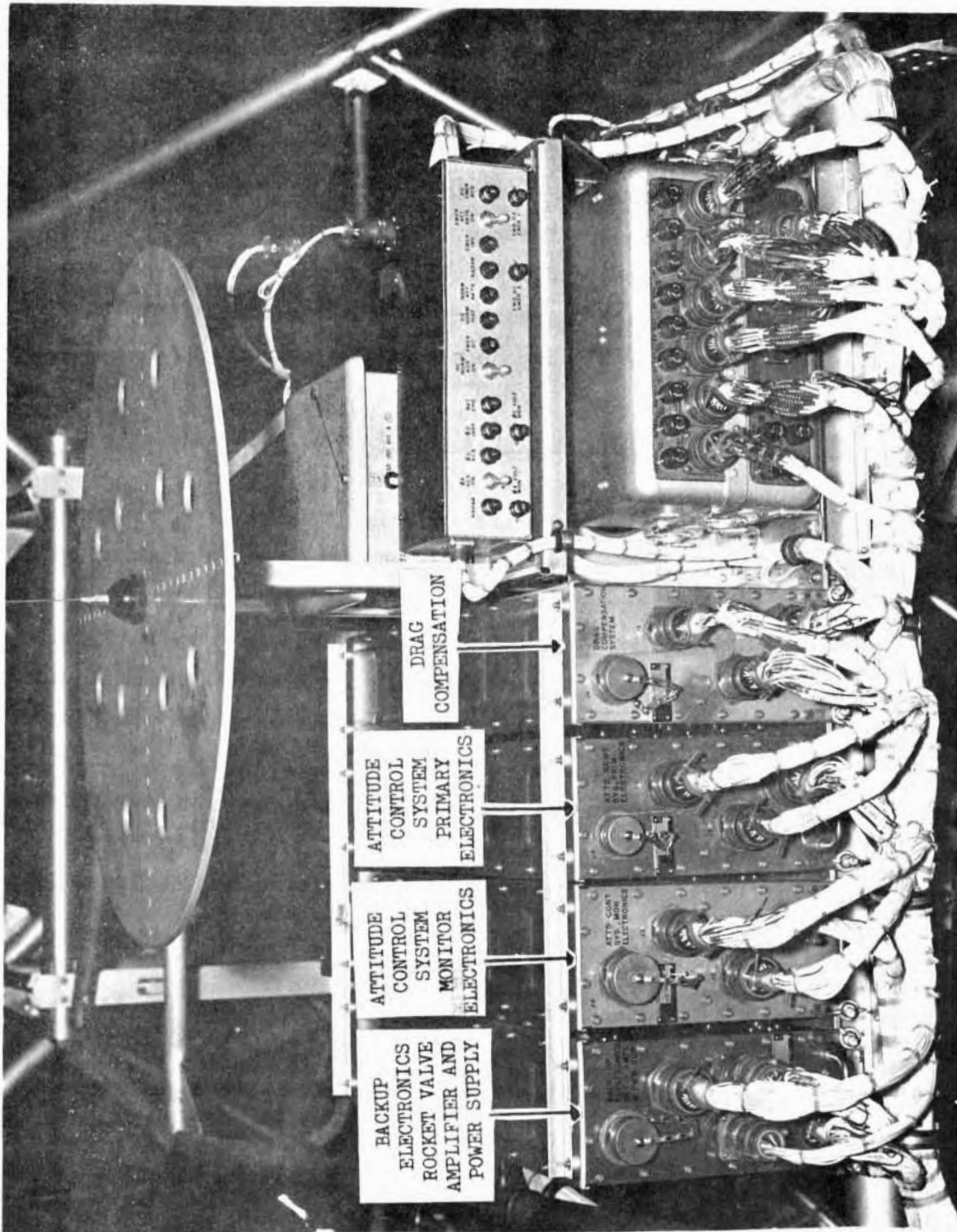


Figure 11-1. Avionics Primary, Monitor, Backup and Drag Compensation Electronics

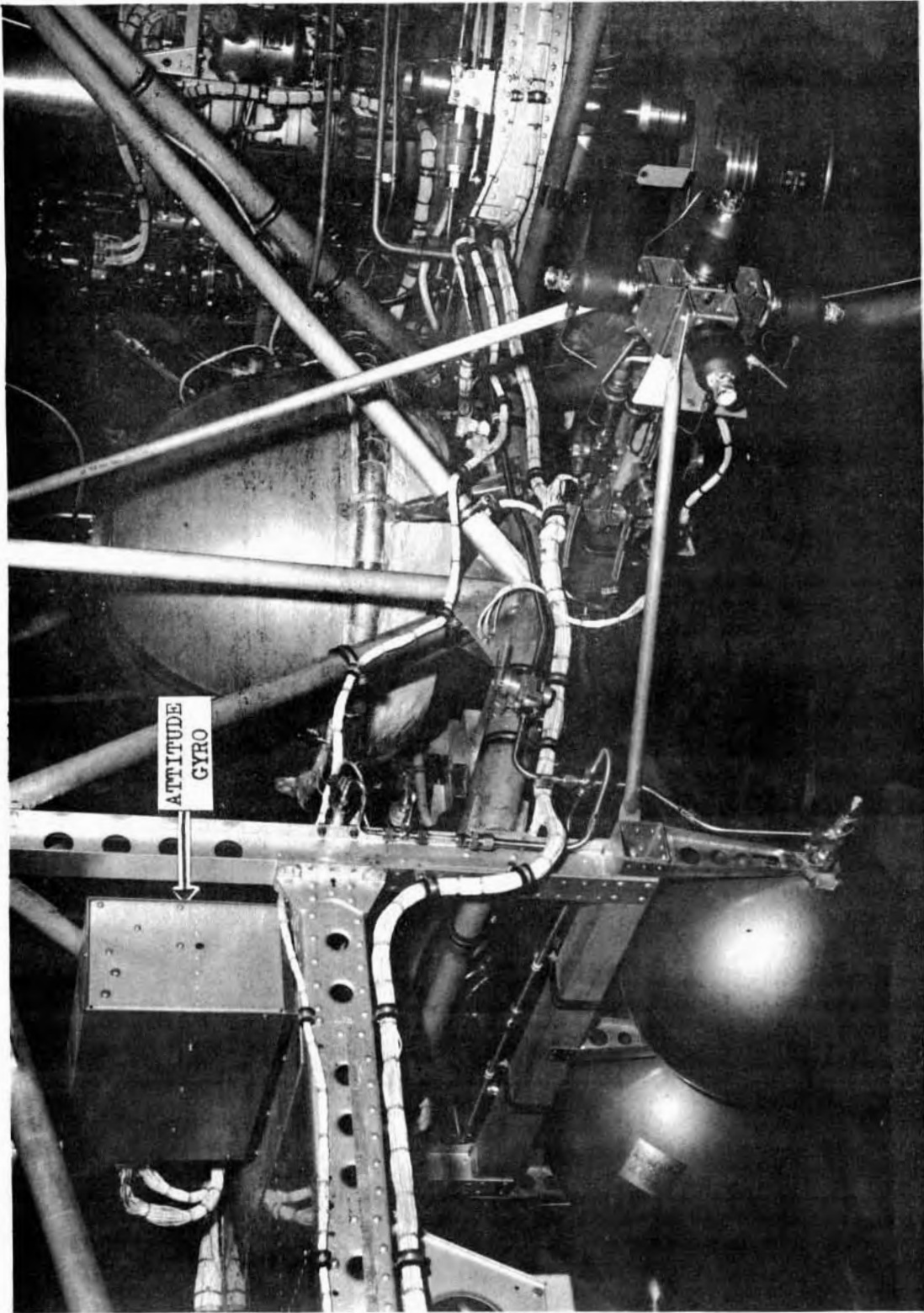


Figure 11-2. Avionics System Attitude Gyro Unit

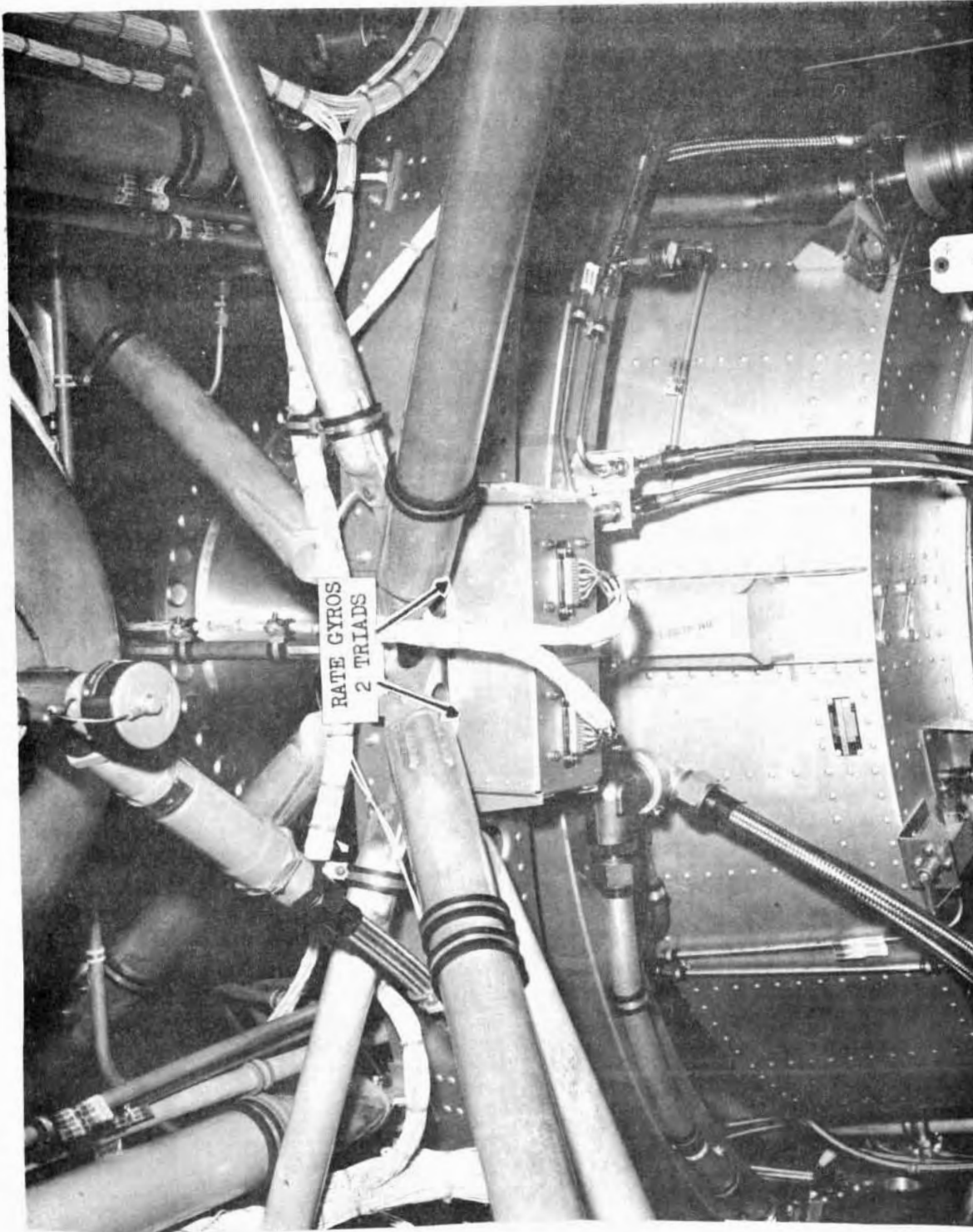


Figure 11-3 Avionics System Rate Gyros

Triads (figure 11-4) and two Gimbal Hydraulic Actuator servo units (pitch and roll). See figure 11-5. The associated equipment and components required for attitude control are miscellaneous switches and solenoids, synchro pickoffs, the auto throttle control, 800-hertz inverter. The Attitude Control Assembly (hand controller-see figure 1-20) provides firing control of the attitude rockets, through the avionics system, in order to maintain vehicle attitude in the pitch, roll and yaw axes as required. The rotational, 3-axes attitude hand controller is GFE and is manufactured by Honeywell for Grumman Aircraft Corporation. Grumman Aircraft report Design Control Specification for Guidance, Navigation, and Control Subsystem Attitude Controller Assembly, Number LSP-300-19B, dated 1 November 1966, details the performance requirements and quality assurance provisions imposed on the manufacturer. The LLTV installation uses three Detent switches, six Pulse Direct switches, a Gimbal Lock switch, and three 800-hertz linear transducers. See Bell drawings 7260-541503 and 7260-541006. The Detent switches (d.p.d.t.) are normally open, capable of switching 500 milliamperes at 28 volts, DC. The Pulse Direct switches (d.p.d.t.) are normally open, capable of switching 1 ampere at 28 volts, DC. The Gimbal Lock switch (s.p.s.t.) is capable of switching 2 amperes at 28 volts, DC. The linear transducer (synchro) has a nominal range of 2.8 volts, rms, for 10 degrees of physical grip rotation. The output of the hand controller is routed to the avionics system to provide input to the various channels. The hand controller, when moved by the pilot against a hardstop, activates relays to place the avionics system in Rate -no Model configuration and results in firing of both sets of rockets. The HARDOVER indicator is also illuminated. The avionics system also, either controls or receives an input from other cockpit indicators and instruments. The flight instruments are the Attitude Indicator (3-axes ball), the H₂O₂ Remaining Indicator, and the Thrust/Weight Indicator. The annunciator panel warning indicators associated with avionics are the AUTO THROTTLE, LOCAL VERTICAL MODE, ENGINE MAX TILT, STABILIZATION MODE, VALVE STUCK, AUTO

PILOT BACK UP and GYRO FAILURE indicators. Refer to section VIII for maintenance instructions for the cockpit instruments. Refer to section V for maintenance instructions on the Hydraulic Gimbal system.

11-6. VEHICLE ATTITUDE CONTROL SYSTEM (ACS)

11-7. The Vehicle Attitude Control system provides the control signals to fire the 16 attitude control rockets to produce control moments in response to pilot commands and/or vehicle motions. Tables 11-1 and 11-2 list the basic attitude control system characteristics. The vehicle attitude control is normally performed with the primary electronics operating in the rate command mode with attitude hold. The mode may be operated with moment compensation (mode 1) or without moment compensation (mode 2). Moment compensation is selected by a switch in the cockpit, and when selected, it is applied to the pitch, roll and yaw channels simultaneously. Independent axis selection is not available.

11-8. A monitor comparator compares the output of the primary electronics channel with that of an equivalent monitor electronics channel and when disagreement exists, the comparator automatically switches control to the rate command back up mode (mode 5). There is a monitor channel and a comparator for each axis. An error detected by either the pitch comparator, or the roll comparator, will switch both pitch and roll to the rate command back up mode simultaneously, since the same attitude rockets control both pitch and roll. The yaw comparator operates independently.

11-9. In addition to the switching commanded by the comparators, control will be switched automatically to the rate command back up mode if the primary rate gyros exhibit an excess rate such as, if the power supply to the primary rate gyro pick-offs fails, if the primary AC or DC power supplies fail, and if the hand controller malfunction detector detects a

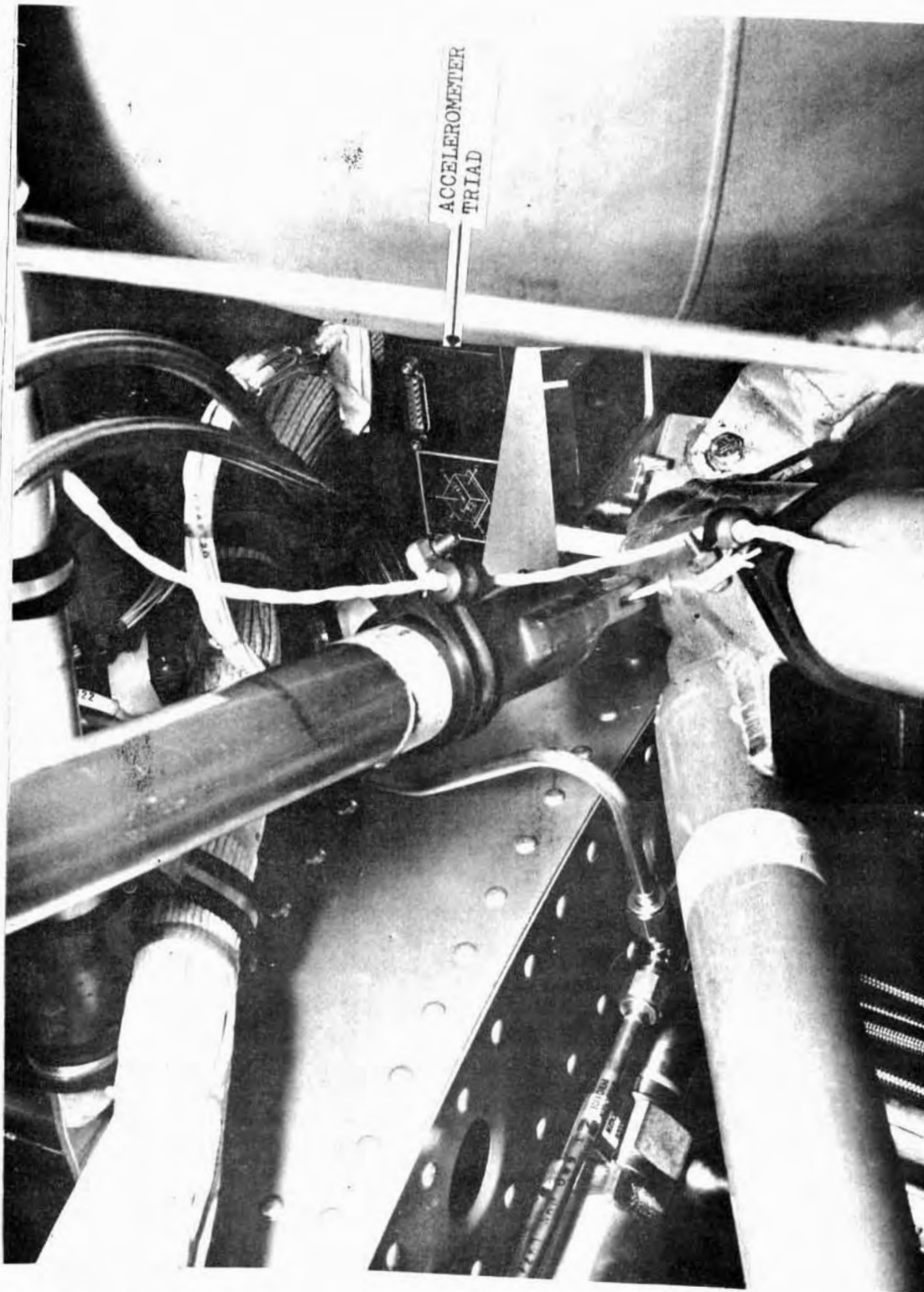


Figure 11-4. Avionics System Accelerometer Triad

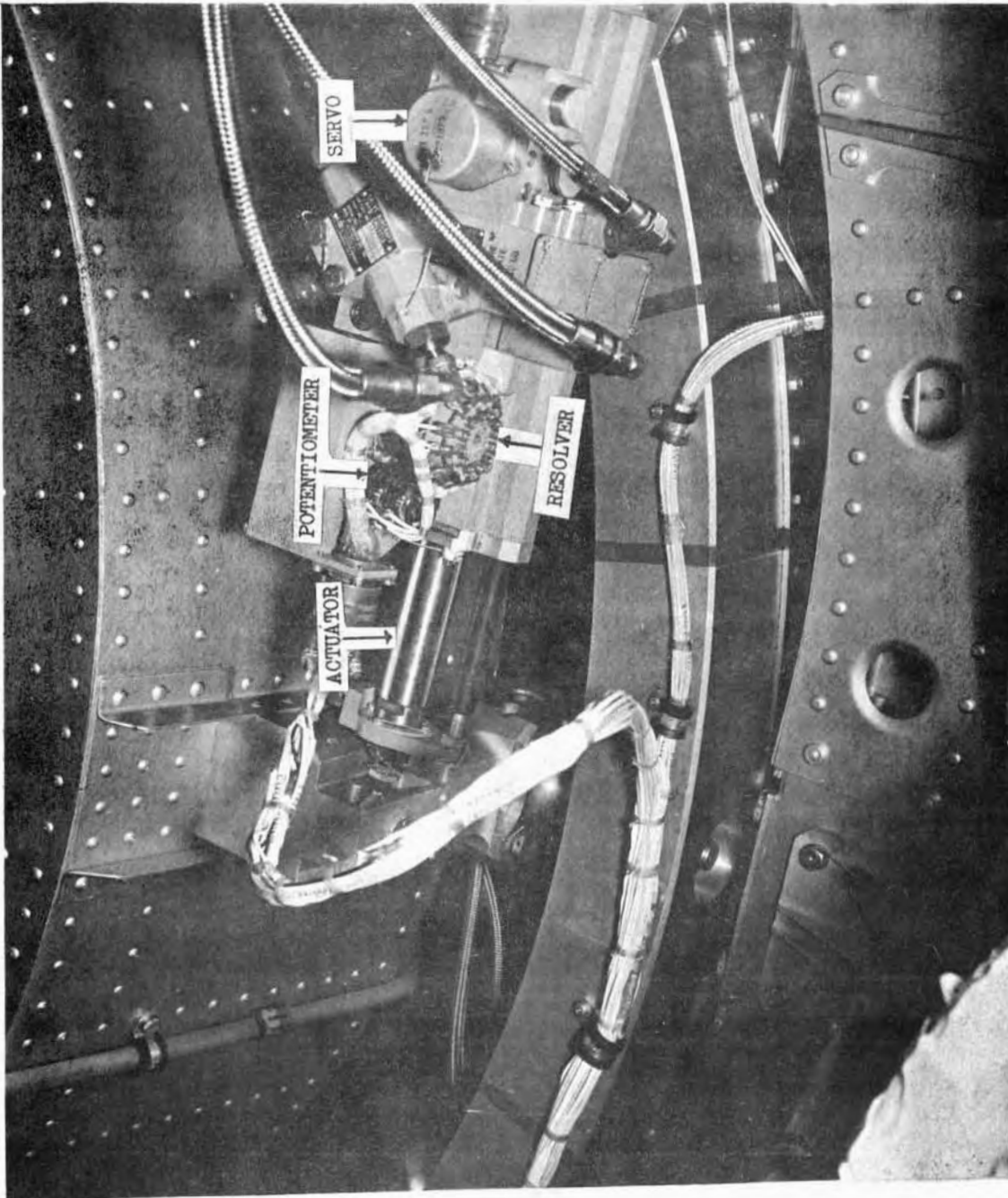


Figure 11-5. Avionics System Typical Gimbal Hydraulic Actuators

failure of the function direct switches in the hand controller (see description of modes 3 and 4 that follows). Again, pitch and roll channels are switched simultaneously and yaw separately.

11-10. The pilot may select the rate command back up mode manually by a switch in the cockpit. In this case, all three axes are selected simultaneously. However, the rate command back up mode does not possess an attitude hold capability, or moment compensation.

11-11. In addition to the rate command modes (modes 1, 2 and 5) already described, primary direct command is available in each of the three axes. The mode is intended for use as an emergency back up system, but may be selected manually by the pilot for familiarization with the mode. Axes may be selected independently by Attitude Control Mode switches located above the hand controller. Three-axes moment compensation may be selected with this mode by actuating the cockpit switch, but this configuration (mode 3) is not used in practice as it serves no useful purpose.

11-12. In the primary direct command mode without model (mode 4), movement of the hand controller $2\frac{1}{2}$ degrees or more, out of the central detent position, commands a vehicle rate of $10.5^\circ/\text{sec}$. This vehicle rate will be sustained until the hand controller is returned to the detent position. In pitch and roll the primary direct command mode has attitude hold and rate feedback. It differs from the primary rate command mode only in that the rate commanded by the pilot is not smoothly adjustable. In yaw there is no attitude hold when the direct mode is manually selected by the pilot. In the primary direct command mode, control will automatically be switched to the rate command back up mode, if the primary rate gyros exhibit an excess rate.

Table 11-1. Attitude Control System Characteristics

| Mode | Max Angular Rate Command | Angular Rate Threshold | Drift in Attitude Hold | Attitude Threshold | Angular Acceleration |
|-----------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1. Primary-Rate Command with Attitude Hold and Model* *Model is portion of moment compensation system. | Adjustable from $\pm 10^\circ/\text{sec}$ to $\pm 20^\circ/\text{sec}$. Each axis is independent, exclusive of Hand Controller | Adjustable from 0.2 to $2^\circ/\text{sec}$. Each axis independent, exclusive of Rate Gyro. | Average drift shall be $0.5^\circ/\text{min}$ for pitch and roll $1.25^\circ/\text{min}$ yaw. These values are max Includes Gyros See Note 4. | Adjustable from 0.3 to 1.5° Each axis independent exclusive of Attitude Gyros. | Average acceleration adjustable from 4 to $12 \pm 0.5^\circ/\text{sec}^2$. See Note 1 and 2 for peak acceleration and Note 3 for conditions for 2 Jet and 4 Jet logic |
| 2. Primary-Rate command with Attitude Hold-no Model | Same as (1) | Same as (1) | Same as (1) | Same as (1) | as per Note 1 and 2 |
| 3. Primary-Direct with rate feedback, attitude hold and model | N/A | N/A | N/A | N/A | Same as (1) |
| 4. Primary-Direct with rate feedback, attitude hold & no model | $10.5^\circ/\text{sec} \pm 0.5/\text{sec}$ | Same as (1) | Same as (1) | N/A | Same as (2) |
| 5. Backup-Rate command | Same as (1) | Same as (1) | N/A | N/A | Same as (2) |

NOTES:

- Axis 60 lb Thrusters Peak Acceleration 90 lb Thrusters
 Pitch 25.3 to 26.9 . . . $^\circ/\text{sec}^2$ (both sets of thrusters std. and test) . . . 38.0 to 40.4
 12.6 to 13.5 . . . (one set of thruster std. or test) 18.9 to 20.2
 Roll 35.8 to 50.3 . . . (both sets of thrusters std. and test) 53.8 to 75.5
 18.0 to 25.2 . . . (one set of thrusters std. or test) 27.0 to 37.8
 Yaw 15.2 to 18.3 . . . (both sets of thrusters std. and test) 22.8 to 27.5
 5.15 to 6.28 . . . (std. set of thrusters) 7.74 to 11.6
 10.0 to 12.2 . . . (test set of thrusters) 15.1 to 18.3
- Peak accelerations shown for both sets of 60 and 90 lb. thrusters. For other sized thrusters, T lbs/thruster, multiply peaks given for 90 lb. for both sets by $\frac{T}{90}$ where both sets are used or by $\frac{T}{180}$ where one set is used.
- When model is used in the rate command mode the system simulates 2 Jet logic when the Model rate error is less than $1 \pm 0.1^\circ/\text{sec}$. Average accelerations are then 1/2 those listed above (4 to 12°sec^2 which are for simulated 4 Jet logic). Simulated 4 Jet logic is effective when the model rate error is greater than $1 \pm 0.1^\circ/\text{sec}$. In the Direct Mode only 4 Jet logic is used.
- Accuracy to be met under:
 a. 70° to 100°F
 b. 20° to 70°F

11-13. If a failure of a hand controller synchro is diagnosed by the hand controller malfunction detector, the axis concerned will automatically be switched to and latched into the primary direct command mode (mode 4). This is necessary to prevent the pilot from attempting to use either of the rate command modes with a faulty synchro.

11-14. PRIMARY ATTITUDE CONTROL SUBSYSTEM

11-15. The primary attitude control subsystem is normally used for an entire mission (including lunar simulation phase). A component block diagram of the primary control system for a typical channel is shown in figure 11-49.

11-16. PRIMARY-RATE COMMAND WITH ATTITUDE HOLD (MODE 2) - In this mode, a vehicle angular rate is commanded proportional to stick deflection when the stick deflection exceeds the hand controller deadband of approximately ± 1.5 degrees. Attitude hold is engaged whenever the stick is in the detent position and the vehicle rate is less than the rate switching value (adjustable from 1 to 3 degrees second).

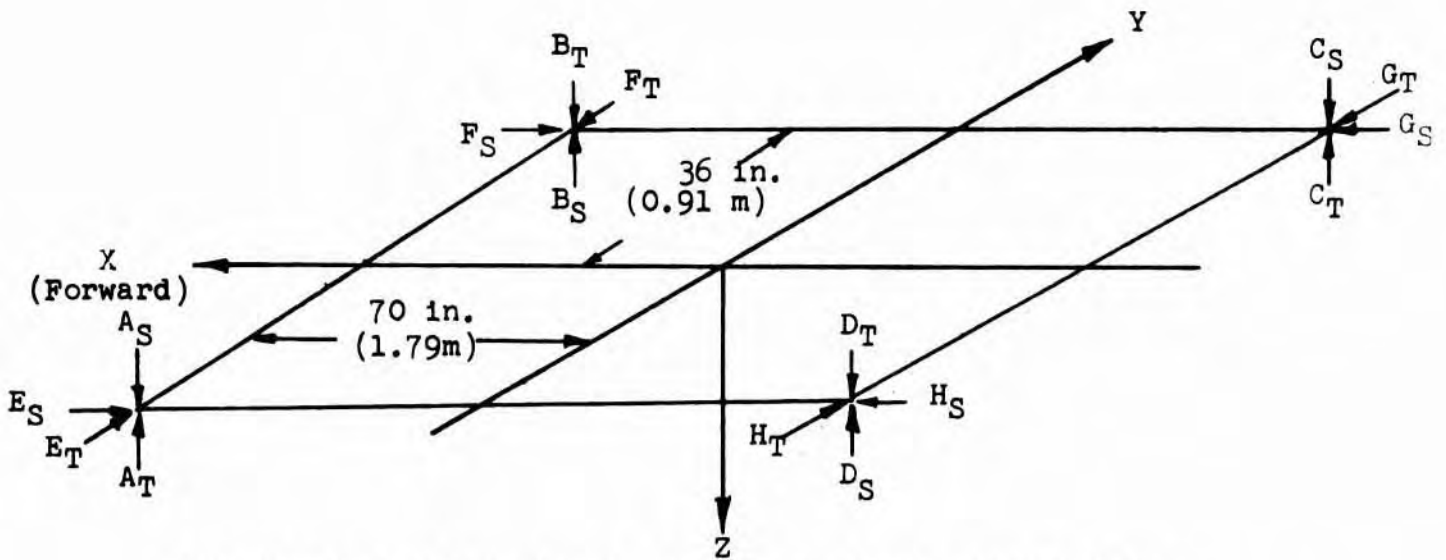
When operating in attitude hold, the vehicle attitude is maintained with an average drift less than $\frac{1}{2}$ degree per minute in pitch and 8 degrees per minute in yaw. There is no option given the pilot for engaging or disengaging the attitude hold feature in primary rate command. When above conditions are met the attitude hold feature is always present in the primary rate command.

11-17. PRIMARY DIRECT COMMAND (ON/OFF MODE) - When the hand controller is moved $2\frac{1}{2}$ degrees or more, in any direction, the attitude rockets will fire until the vehicle rate is $10.5^\circ/\text{sec}$. The vehicle angular accelerations depend upon the number of rockets fired and the rocket thrust levels (ground adjusted). Refer to table 11-1 for accelerations available

in pitch, roll, and yaw. When the controller is returned to the neutral position, the vehicle rate will return to zero, and the attitude hold circuits will hold the vehicle attitude constant in pitch and roll. There is no attitude hold in yaw.

11-18. MOMENT COMPENSATION (MODEL) - When this portion of the system is engaged, the electronic model will command a preset (ground adjusted) vehicle angular acceleration in each axis in response to pilot commands regardless of rocket thruster setting. When the system is operating in the primary rate command mode, an angular rate is commanded proportional to controller deflection. The electronic model will correspondingly command a preset angular acceleration command to acquire the desired rate command by pilot.

11-19. ROCKET THRUSTER LOGIC - The attitude rocket engines fire in an on/off manner according to the logic shown in figure 11-6. Two sets of 8 control rockets each (test and standard) are provided. Either one or both sets may be selected to fire to provide redundancy. For individual pitch, roll, or yaw commands, the system will fire two rockets if the standard or test set is selected, or four rockets if both sets are chosen. For combined pitch and roll commands, however, only one rocket will fire if the standard or test is selected, or two rockets if both sets are chosen. The selection is automatically controlled by the opposing rocket inhibit logic, which prevents opposing rockets from firing at the same time. The system is also designed so a large command in one axis does not result in loss of control in another axis. For example, if, with test rockets selected, a small roll right command is added to a large pitch up command, only rocket A_T shall fire when the roll threshold is exceeded. A_T will continue to fire until the small roll error is reduced to within the roll threshold. D_T will then fire along with A_T until the pitch error is within the pitch threshold. Similar situations exist for other combined commands. (See figure 11-6.)



Rockets with subscript S denote standard rockets fire.
 Rockets with subscript T denote test rockets fire.
 For dual-system operation, both standard and test rockets fire.

| Rocket | AS | AT | BS | BT | CS | CT | DS | DT | ES | ET | FS | FT | GS | GT | HS | HT |
|---------------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Pitch Up | | X | X | | X | | | X | | | | | | | | |
| Pitch Down | X | | | X | | X | | | | | | | | | | |
| Roll Right | | X | | X | X | | X | | | | | | | | | |
| Roll Left | X | | X | | | X | | X | | | | | | | | |
| Yaw Right | | | | | | | | | X | X | X | X | X | X | X | X |
| Yaw Left | | | | | | | | | | | X | X | X | X | X | X |
| Pitch up and Roll right | | X | | | X | | | | | | | | | | | |
| Pitch up and Roll left | | | X | | | | X | | | | | | | | | |
| Pitch down and Roll right | | | | X | | | X | | | | | | | | | |
| Pitch down and Roll left | X | | | | | X | | | | | | | | | | |

Figure 11-6. Attitude Control-Rocket Firing Logic

11-20. PRIMARY ELECTRONICS BLOCK DIAGRAM ANALYSIS - The stages used in the pitch, roll, and yaw attitude channels are very similar if not identical. A block diagram analysis (see figure 11-49) is presented for a typical channel in order to minimize repetition. In areas of significant variation, an analysis is presented.

11-21. The initial analysis assumes a selection of attitude control mode in rate with model and for reference the pitch channel is described. An 800-hertz, AC signal from the hand controller synchro is applied to the rate command circuit in the primary and monitor subsystems. If the AC signal voltage is greater than 2.8 vrms (20 degrees per second), the amplifier will saturate. The rate command circuit converts the AC signal by amplification, demodulation, filtering and amplification to a DC signal. At maximum command (20 degrees per second), this should be 10 volts DC.

11-22. The output of the rate command circuit is applied through the de-energized contacts of K6C to the rate model and model lead circuits. The rate model circuit generates a signal with an adjustable linear rate of change (acceleration), which is used to force the vehicle rate change to the same magnitude. The attitude rocket system, through the rate feedback path attempts to create zero difference between the model and rate gyro outputs. The model lead circuit provides a rocket command pulse in advance of the rate model signal, thus preventing a feeling of lag between pilot's command and rocket firing. This lag would occur, without a lead circuit, since the rate model amplifier's output is of a ramp form and must integrate up to the threshold magnitude before providing a rocket firing command. For rate with model operation, relay K7 is also de-energized, and the rate model and model lead outputs are applied to the threshold amplifier through a summing network. Under no model conditions, the rate command signal is applied directly to the threshold amplifier through the summing network.

11-23. A selection of attitude control mode to direct with model energizes K6 and routes the output from the hand controller direct switches to the direct model circuit. Relay K7, being de-energized, routes this output to the negative input side of the same integrator amplifier that is used in the rate model circuit. However, a feedback loop is not employed around the model. This difference enables the model integrator to have a memory and maintain an output after the 3-axes hand controller signal has returned to zero. This allows the vehicle to simulate a zero aerodynamic friction or damping environment, and hence maintain a fixed rate after receiving a pulse direct command. The mode is not normally used.

11-24. A pitch rate 400-hertz, AC signal from the primary rate gyro is applied to the rate gyro feedback circuits in the primary and monitor subsystems. This signal is nominally 3.0 vrms for a 20 degree per second pitch rate change. The rate gyro feedback circuits convert the AC signal by demodulation, filtering, and amplification to a maximum 10 volts DC. An input greater than 3.0 volts AC saturates the amplifier. The rate gyro feedback output signal is routed to the threshold amplifier input.

11-25. The attitude gyro, with synchro pickoffs, provides a 400-hertz, AC signal to the attitude gyro feedback circuit and the 3-axes attitude indicator. Refer to section VIII for maintenance instructions on the attitude indicator. The AC signal is nominally 206 millivolts RMS per degree. The AC signal is converted to DC by demodulation, filtering and amplification. This DC signal is applied to the attitude hold and synchronizer circuit. The attitude hold and synchronizer has the following functions: (1) maintains an attitude reference and computes the vehicle attitude error during attitude hold (no pilot commands) periods, (2) updates the attitude reference during a command maneuver, and (3) establishes the ratio of rate to attitude error feedback signals which controls the attitude rocket firing commands.

11-26. Dependent upon the attitude control mode selected, the appropriate signals are routed to the threshold amplifier circuitry. All signals, except direct with no model signals, are applied to a resistive summing network and then to the threshold amplifier. In the direct no model mode (mode 4), the output of the Function Direct switches is applied, after attenuation, to the non-inverting input of the threshold amplifier. The threshold amplifier circuit functions as a summing amplifier for the various control signals and creates a deadzone or threshold for the attitude control system. The inverter circuit converts a negative 10-volts DC output from the threshold amplifier to a positive 10-volts DC, which is applied to the rocket logic. To ensure that both the primary and monitor threshold amplifiers switch together, an assist circuit feeds a signal from the primary threshold amplifier's output to the positive input of the monitor channel threshold amplifier.

11-27. The roll primary electronics circuitry is identical to the pitch axis circuitry so far as the rate gyro, attitude gyro, model circuit, threshold amplifier, and inverter amplifier are concerned. The outputs of the pitch and roll (primary) threshold inverter amplifiers are applied to the pitch and roll "opposing rocket inhibit" logic circuits. These circuits prevent two opposing rockets from firing simultaneously. This is necessary since the rockets are mounted on diagonal corners of the vehicle and if more than two rockets fire at a time, they cancel one another's moments, while consuming more fuel. The outputs from the pitch and roll "opposing rocket inhibit" logic circuits are routed to the correct jet rocket power amplifier. A pair of rockets (one set selected - test or standard) are always fired for a single axis maneuver and only one rocket during a combined pitch/roll maneuver. There are 16 rocket solenoid driving amplifiers, each consisting of a pre-amplifier and a power amplifier, which are connected as a darlington amplifier. The rocket firing signals are then fed through appropriate relay contacts to the rockets. The rocket

firing signals are also routed to the comparator in the monitor electronics subsystem.

11-28. The yaw attitude channel circuits are similar in operation to the pitch and roll channels. The exceptions are the yaw rate gyro and yaw attitude gyro circuits. The yaw rate gyro signal is applied to stages similar to the pitch and roll channels. However, the yaw rate switching circuits and 2-jet/4-jet logic circuits are physically located with the yaw primary electronics. In addition the yaw rate gyro feedback circuit output signal is applied to a yaw attitude hold and synchronizer circuit. This circuit has the following functions: (1) computes the vehicle attitude error during attitude hold (no pilot commands) periods, (2) resets the attitude error to zero during a commanded maneuver and (3) establishes the ratio rate to attitude error feedback signal which controls the attitude rocket firing commands. The yaw rate gyro feedback signal and the attitude hold and synchronizer signal is applied to the yaw threshold amplifier through a resistive summing network.

11-29. The yaw attitude gyro signal is used primarily for instrumentation and does not feed back a signal to control rocket firings or attitude hold as does the pitch and roll attitude gyro. The signal is applied to a control differential transformer in the cockpit which allows the pilot to set the desired heading on the 3-axes attitude indicator. See figure 8-9.

11-30. The attitude yaw gyro synchronizer rate switching circuit monitors the rate gyro output and energizes a switching relay whenever the rate exceeds a preset quantity of 1 to 3 degrees per second. The relay contacts enable the attitude synchronizer to update its attitude reference.

11-31. The 2-jet/4-jet switching circuit is designed to energize relay K1, whenever the absolute value of the difference between the synchro (hand controller) command and the model output is greater than approximately 1 degree per second.

11-32. BACKUP ATTITUDE CONTROL SUBSYSTEM (MODE 5)

11-33. The electronic system provides a rate backup control system. In this mode vehicle angular rates are commanded proportional to stick deflection. The backup system contains separate wiring, independent power supplies, and rate gyros. The system employs the same rockets used by the primary system. Figure 11-49 provides a block diagram of the backup attitude control system. The backup system should only be used in the event of a malfunction in the primary system. The backup system is not checked by the monitor comparator subsystem and there is no provision for automatic (electronic) switching from backup to primary in the event of malfunction in the backup system. If necessary, the pilot may select the backup mode for a short period of time, however, to determine that the backup mode is operating properly. The AUTO PILOT BACK UP warning indicator illuminates when the ACS is either automatically or manually switched to backup mode.

11-34. BACKUP ELECTRONICS ACS BLOCK DIAGRAM ANALYSIS - The pitch, roll, and yaw backup electronics ACS circuits are identical, therefore only the pitch channel is discussed. The same signal from the hand controller synchro that is used for the primary electronics is routed to the backup rate command circuit. A separate backup pitch rate gyro feeds a signal to the rate gyro feedback circuit and a pitch rate gyro excess rate detector. The backup electronics does not have a model (moment compensation) feature. The operation of the circuitry for the rate command, rate gyro feedback, threshold and inverter amplifiers and the rocket amplifiers is the same as

for the equivalent circuits in the primary electronics. The same rockets are used by relay switching action.

11-35. The gyro excess rate detector monitors the output of the rate gyro and energizes an emergency relay whenever the rate exceeds a preset quantity. The 400-hertz, AC rate gyro signal is rectified, filtered and amplified, which provides an AC signal to a trigger amplifier, which has a preset threshold. An excessive rate triggers this stage which energizes the emergency relay and illuminates the BU GYRO FAIL indicator in the cockpit.

11-36. MONITOR SUBSYSTEM

11-37. Monitor comparator, excess rate, and hand controller malfunction detection circuits are used to monitor operation of the primary-rate and primary-direct attitude control modes (figure 11-49). These are automatically engaged whenever the ACS primary system is selected. Table 11-2 summarizes the logic of the detection circuits.

11-38. MONITOR COMPARATOR - An "electronic equivalent of the primary mode electronics" (also referred to as the monitor channel electronics) (see figure 11-49), generates equivalent rocket firing signals in the same manner as the primary electronics. The primary and monitor signals are both applied to the monitor comparator. When the monitor comparator determines that disagreement exists between the primary and monitor channels in any axis, the monitor automatically switches the electronics to the rate backup mode. Switching is accomplished within 0.5 seconds. Pitch and roll are switched together, and yaw is switched separately. A failure matrix has been generated for the conditions which the monitor comparator has to satisfy. From this failure matrix, the logic equation required to satisfy the failure matrix has been established. The logic

Table 11-2. Typical Pitch Channel Logic

| Case | Indications | | Probable Failure | Primary Modes | | | | Backup Rate | Cockpit Indication |
|---------------------------|----------------------------|-----------------------------|------------------|--------------------|----------|--------|----------|-------------|--------------------|
| | Prime R. G. 25 ± 1°/sec | Backup R. G. 25 ± 1°/sec | | Rate/Attitude Hold | | Direct | | | |
| | | | | Model | No Model | Model | No Model | | |
| Excess Rate Detection | | | | | | | | | |
| 1 | Yes | N. A. | Pri. R. G. | 0 | | | X | X | BUL |
| 2 | Yes | N. A. | Pri. R. G. | | 0 | | X | X | BUL |
| 3 | Yes | N. A. | Pri. R. G. | | | 0 | X | X | BUL |
| 4 | Yes | No | Pri. R. G. | | | | 0 | X | NONE |
| 5 | N. A. | Yes | Bkup. R. G. | 0 | | | X | | RGL |
| 6 | N. A. | Yes | Bkup. R. G. | | 0 | | X | | RGL |
| 7 | N. A. | Yes | Bkup. R. G. | | | 0 | X | | RGL |
| 8 | N. A. | Yes | Bkup. R. G. | X | | | 0 | X | RGL |
| Hand Controller Detection | | | | | | | | | |
| 9 | N. A. | N. A. | Stick Syn. | 0 | | X | X | | BUL |
| 10 | N. A. | N. A. | Stick Syn. | | 0 | | X | | BUL |
| 11 | N. A. | N. A. | Dir. Sw. | X | | | 0 | X | BUL |
| 12 | N. A. | N. A. | Dir. Sw. | X | | | 0 | X | BUL |

0 = Present Mode

X = Possible Safe Emergency Modes

X = Selected Emergency Mode

R. G. - Rate Gyro

BUL - Auto Pilot Backup LT

RGL - Backup Rate Gyro Failure LT

N. A. = Not Applicable

equation has been implemented into active circuitry in the monitor comparator.

11-39. EXCESS RATE DETECTION CIRCUITRY - The excess rate detection circuitry provides automatic switching and cockpit displays which function as indicated by the primary or backup rate gyro. These functions, according to operating condition, include the following:

- A. With the system operating in the rate command mode with or without model, if the primary rate gyro indicates a vehicle rate of $25 \pm 1^\circ/\text{sec}$, the system is automatically switched to rate backup and the AUTO PILOT BACK UP indicator is illuminated.
- B. With the system operating in the direct mode with model, if the primary rate gyro indicates a vehicle rate of $25 \pm 1^\circ/\text{sec}$, the system is automatically switched to rate backup and the AUTO PILOT BACK UP indicator is illuminated.
- C. With the system operating in the direct mode with no model, if the primary rate gyro indicates a vehicle rate of $25 \pm 1^\circ/\text{sec}$, the system is automatically switched to rate backup and the AUTO PILOT BACK UP indicator is illuminated.
- D. In all modes, if the backup rate gyro indicates a vehicle rate of $22^\circ/\text{sec}$, the BU GYRO FAIL indicator illuminates. The excess rate detection circuitry for all channels is similar to that discussed in paragraph 11-29 (see figure 11-35).

11-40. HAND CONTROLLER MALFUNCTION DETECTION CIRCUITRY - The hand controller operates a synchro and two direct switches: (1) logic direct and (2) direct function. The conditions where hand controller malfunctions may be encountered and the associated effects, switching and indications, are:

- A. Open Synchro - With the system in the rate command mode with or without the model, if the logic direct switch is actuated and the corresponding synchro output is not present, the system automatically switches to the primary-direct model(no model) as an emergency mode and the AUTO PILOT BACK UP indicator illuminates.
- B. Hardover Synchro - With the system in the rate command mode with or without model, if a synchro output exists which is greater than that equivalent to the logic direct switch position and the direct function switch has not been actuated, the system automatically switches to the primary direct mode (no model) as an emergency mode and the AUTO PILOT BACK UP indicator illuminates. As in open synchro (1), the monitor comparator takes precedence over this circuitry. Switching is accomplished within 0.5 seconds.
- C. Direct (LDS) Switch Failure - With the system in a rate mode, if either direct switch fails, the automatic switching to primary direct mode will be inhibited. The pilot can still manually select the primary direct mode, but if he does, the system will automatically switch to rate backup and the AUTO PILOT BACK UP indicator will illuminate.
- D. Direct (FDS) Function Switch Failure - With the system in the direct mode with or without model, if the direct function switch fails, the system automatically switches to rate backup and the AUTO PILOT BACK UP indicator illuminates. Switching is accomplished within 0.3 seconds. This will not happen if the hand controller has been deflected more than 4.5 degrees.

11-41. PRIMARY RESET SWITCH - In the event the monitor comparator subsystem automatically switches the ACS from primary to rate backup as a result of spurious signals emitted by either the primary or monitor channel but in fact the two systems are operating satisfactorily, the pilot is able, with Moment Compensation switch OFF, to manually switch the ACS from backup to primary by momentarily actuating the AFCS Primary Reset switch on the left console. Caution must be exercised in the use of the AFCS Primary Reset switch, inasmuch as the pilot cannot be completely sure that the primary system is working properly. During normal operation reset will be attempted on the ground.

11-42. VALVE STUCK WARNING - Rocket chamber pressure transducers serve as sensors for the stuck valve circuit. The circuit monitors the rockets to determine if opposing rockets are firing. Simultaneous firing of any of the pairs of rocket combinations would imply a stuck-open valve.

11-43. MONITOR ELECTRONICS BLOCK DIAGRAM ANALYSIS - As the roll, pitch, and yaw attitude controls channels are very similar and in some instances are identical, only one channel will be discussed. Circuits similar to the gyro excess rate monitor, the rate switching and 2-jet/4-jet circuits are discussed in paragraphs 11-30, 11-31, and 11-35 respectively. The monitor comparator and hand controller malfunction detector (HCMD) circuits are applicable to primary electronics only.

11-44. The monitor channel comparator circuit continuously monitors four signals from the ACS system and determines if any failure has occurred in either the monitor or primary channel electronics. The four signals are (1) the Primary Channel jet logic output signal, (2) the Monitor Channel jet logic output signal, (3) the Standard Rocket solenoid amplifier output signal (low side of rocket solenoid), and (4) the Test rocket solenoid amplifier output signal. All signals are binary, but the two

rocket solenoid signals are at different levels than the two jet logic command signals. Each pair of Pitch/Roll rockets has a similar comparator circuit resulting in four Pitch/Roll comparators; whereas yaw requires only two circuits. If either a Pitch or Roll comparator senses a malfunction, the system is switched to backup in both the Pitch and Roll axis; however, a yaw malfunction results in only the yaw axis being switched.

11-45. The hand controller malfunction detector (HCMD) is designed to detect hardover or open conditions in either the 3-axes hand controller's linear transformer (synchro) or functional direct switch (FDS) and switch the ACS system (single axis) to a safe backup mode. This is accomplished by comparing three pieces of information (signals) from the hand controller in two separate detection circuits. One circuit compares the synchro signal with a logic direct switch (LDS) signal and is the synchro/direct switch comparator. The LDS is the same type switch as the FDS, except it is not used for firing rockets or controlling the vehicle; it is only used in the HCMD logic circuits. The other circuit compares the two direct switch signals, LDS and FDS, and is the direct switch comparator.

11-46. The stuck valve detector senses when any of eight pairs of opposing rockets are firing, and after a fixed time delay energizes the stuck valve relay. This is accomplished by monitoring each of the five kilohm attitude rocket pressure transducer potentiometers with two input diode "AND" circuits. The output of each "AND" circuit is then "OR'd" into the input of a trigger circuit. Simultaneous firing of any of the following rocket combinations would imply a stuck-open valve.

| <u>Pitch-Roll</u> | | <u>Yaw</u> | |
|-------------------|-------------|-------------|-------------|
| SS | TS | SS | TS |
| $A_S - C_S$ | $D_T - B_T$ | $E_T - H_T$ | $E_S - H_S$ |
| $B_S - D_S$ | $A_T - C_T$ | $F_T - G_T$ | $F_S - G_S$ |

If, for example, A_S is stuck open, a pitch down, roll left condition results. To counteract this, the ACS commands a pitch up, roll right by firing C_S . Thus, both A_S (stuck open) and C_S are firing simultaneously, which is an illegitimate firing command. The stuck valve circuit would detect this as a stuck valve condition. In the event of a stuck valve indication, the logic will hold for a period of approximately 230 milliseconds before illuminating the VALVE STUCK indicator in the cockpit. This allows response time of the rocket firing coils, and prevents rocket thrust decay caused by a previous ACS command from falsely indicating a stuck valve.

11-47. ACS INSTRUMENTATION - A 3-axes ball Attitude indicator displays vehicle pitch, yaw, and roll attitudes during flight. An AUTO PILOT BACKUP red warning indicator illuminates when vehicle ACS is switched to a rate command backup mode or latched into a primary direct mode. A GYRO FAILURE red warning indicator illuminates when the excess rate detector senses a rate in excess of $25 \pm 1^\circ/\text{sec}$ from the backup rate gyro. A VALVE STUCK warning indicator illuminates if an ACS rocket valve is stuck open. The above cockpit instrumentation is also recorded by the ground station.

11-48. JET ENGINE ATTITUDE CONTROL SYSTEM

11-49. The jet engine attitude control system performs in five selected modes of operation: Manual or Emergency Gimbal Locked, Local Vertical, Engine Centered, and Lunar Simulation mode (jet stabilization). A simple block diagram of the latter three modes is shown in figure 11-7. Table 11-3 lists all the modes of operation and respective conditions of use. For flight safety, one mode has priority over another. Figure 11-8 is a block diagram showing major components of weight/drag, jet stabilization, and auto throttle electronics.

11-50. MODE PRIORITY

11-51. For flight safety, the modes have the following priority. The Gimbal Lock mode, whether the pilot or automatically selected, overrides all other modes. When the vehicle is on the ground or when the jet engine deflects more than $15 \pm 1^\circ$ from the vertical (including in the Lunar Simulation mode), the Local Vertical mode shall be automatically actuated and override all modes except the Gimbal Locked mode. If the jet engine deflects more than $15 \pm 1^\circ$ from Local Vertical and the Local Vertical mode is not automatically selected within 0.35 to 1.0 second, the system shall automatically switch to the Emergency Gimbal Locked mode. If no mode has been selected and the vehicle is airborne, momentarily depressing the Local Vertical Release button shall place the system in the Engine Centered mode.

11-52. GIMBAL LOCK MODE

11-53. In this mode, the jet engine is held in alignment with the vertical or Z axis of the vehicle. The engine gimbal hydraulic actuators are fitted with pressure inlets which, when pressurized hydraulically, cause the actuators to lock in a central position. Under normal conditions, the mode is selected by the pilot by means of a switch on the hand controller, and the locking pressure is supplied from the hydraulic pump on the jet engine. The green gimbal lock mode indicator becomes illuminated.

11-54. If, when the mode is selected by the pilot, pressure fails to rise in the gimbal lock line, then the actuator gimbal lock inlet port becomes automatically pressurized from an hydraulic accumulator source, charged previously while the vehicle was on the ground. This is the emergency gimbal lock mode and causes the red "emergency gimbals locked" warning indicator to illuminate. The green mode indicator will not extinguish, but the mode will have been overridden by the emergency mode.

11-55. If, at any time, and with the Gimbal Lock switch in either position, the engine hydraulic pressure source drops below 1300 psi, the emergency mode is actuated and the red warning indicator illuminates.

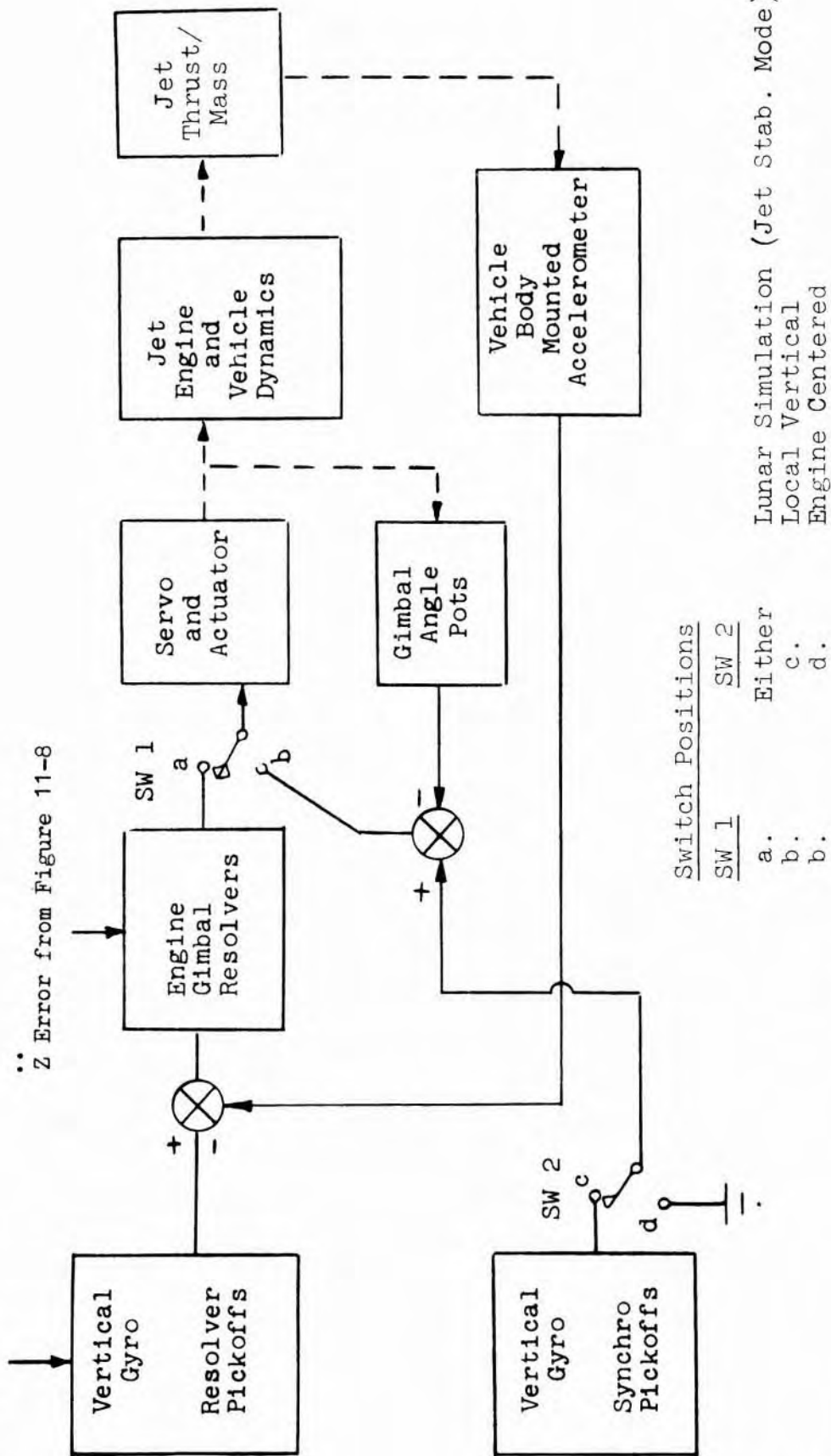
11-56. With the Gimbal Lock switch in the OFF position, if the vehicle 28 vdc normal supply fails, or if the 115 volt 400 H₃ primary AC power fails, then the gimbals will lock immediately from the engine hydraulic supply and the emergency indicator will illuminate. If the fault remains for 0.3 second, then a latching relay will cause the engine to remain in this mode.

11-57. With the Gimbal Lock switch in the OFF position, and the angle between the engine axis and local vertical remains in excess of 15 degrees ($\pm 1.0^\circ$) for 0.3 second in either pitch or roll, then the gimbals will be locked from the engine hydraulic supply and the latching relay will close.

11-58. If the jet engine is not running when the vehicle is on the ground, pressures will be low and the red Emergency Gimbal Lock warning indicator will be illuminated. Since this emergency mode is latched, the indicator will remain illuminated after jet engine start. An Emergency Gimbal Lock reset button, located on the circuit breaker panel, was provided so that the system can be reset to normal. This reset button is not used in flight.

11-59. GIMBAL LOCK MODE BLOCK DIAGRAM ANALYSIS - When the Gimbal Lock switch, located on the hand controller, is placed in the ON position, positive 28 volts DC from the emergency bus is applied to the GIMBAL LOCK MODE indicator on the annunciator panel and to the gimbal lock warning diode box. The 28 volts is coupled through blocking diodes to the gimbal lock solenoid. This places the jet engine in the Gimbal Locked configuration. When the vehicle is not in manual gimbal lock,

5/6 g
Command



Switch Positions

| SW 1 | SW 2 |
|------|--------|
| a. | Either |
| b. | c. |
| b. | d. |

Lunar Simulation (Jet Stab. Mode)
Local Vertical
Engine Centered

Figure 11-7. Jet Engine Attitude Control System

Table 11-3
Jet Engine Modes of Operation

| Title | Conditions of Use |
|-------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Emergency Gimbal Locked | <ol style="list-style-type: none"> <li data-bbox="665 325 1430 595">1. Avionics will automatically select this mode if the engine angle exceeds 15 degrees from local vertical for greater than 0.5 seconds, nominally. Indication to the pilot is illumination of the EMERG. GIMBALS LOCKED red warning indicator. <li data-bbox="665 631 1430 998">2. Low primary hydraulic system pressure (1350 ± 50 psig) sensed by the hydraulic pressure switch will open the emergency solenoid valve allowing accumulator pressure to flow to the gimbal actuators, thus centering the engine. Indication to the pilot is illumination of the EMERG. GIMBALS LOCKED red warning indicator. <li data-bbox="665 1034 1430 1304">3. Primary AC failure will cause avionics to switch to Rate Backup and switch engine attitude control to this mode. Indication to the pilot will be illumination of the AC FAILURE, AUTO PILOT BACK UP, and EMERG. GIMBALS LOCKED indicators. <li data-bbox="665 1341 1430 1610">4. Primary DC failure will cause the avionics to switch to Rate Backup and switch engine attitude control to this mode. Pilot indications will be illumination of the DC FAILURE, AUTO PILOT BACK UP, and EMERG. GIMBALS LOCKED indicators. <p style="text-align: center;"><u>CAUTION</u></p> <p style="text-align: center;">If actuated, this mode should only be released on the ground.</p> |

Table 11-3 (Continued)

Jet Engine Modes of Operation

| Title | Conditions of Use |
|-------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Gimbal Lock | <p>1. This mode overrides all other modes. It may be activated under any of the following conditions:</p> <ul style="list-style-type: none">a. Pilot may select Gimbal Lock mode using the Gimbal Lock switch on the 3-axes hand controller. Indication to the pilot is illumination of the GIMBAL LOCK MODE green status indicator. <p style="text-align: center;"><u>NOTE</u></p> <p>This mode is normally used for takeoff. It locks the gimbal actuators hydraulically, aligning the jet engine with the Z-axis.</p> <ul style="list-style-type: none">b. To disengage this mode, the pilot places the Gimbal Lock switch to OFF. |

Table 11-3 (Continued)

Jet Engine Modes of Operation

| Title | Conditions of Use |
|-----------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Lunar Simulation (Jet Stabilization) | <ol style="list-style-type: none"> 1. Characteristics of this mode are: <ol style="list-style-type: none"> a. Jet engine auto throttle supports 5/6th vehicle weight. b. Jet engine automatically gimballed to provide equal and opposite force to counteract horizontal vehicle drag. c. Lift rockets are used to control altitude and horizontal translations. 2. Activates when all of the following occur: <ol style="list-style-type: none"> a. Lunar Simulation switch is placed in the LUNAR SIM position. b. Lift Rocket T-handle is raised to command a firing where chamber pressure is greater than 100 psia. c. Gimbal Lock and Local Vertical switches are OFF. d. Jet engine angle is less than 16 degrees from local vertical. 3. Deactivated normally by: <ol style="list-style-type: none"> a. Depressing SIM REL pushbutton on Jet Throttle. b. Advancing Jet Throttle. c. Placing Lift Rocket T-handle down to OFF. d. Placing Gimbal Lock switch to ON. |
| Engine Centered | <ol style="list-style-type: none"> 4. This mode is in operation when no other mode has been selected and the vehicle is airborne. |

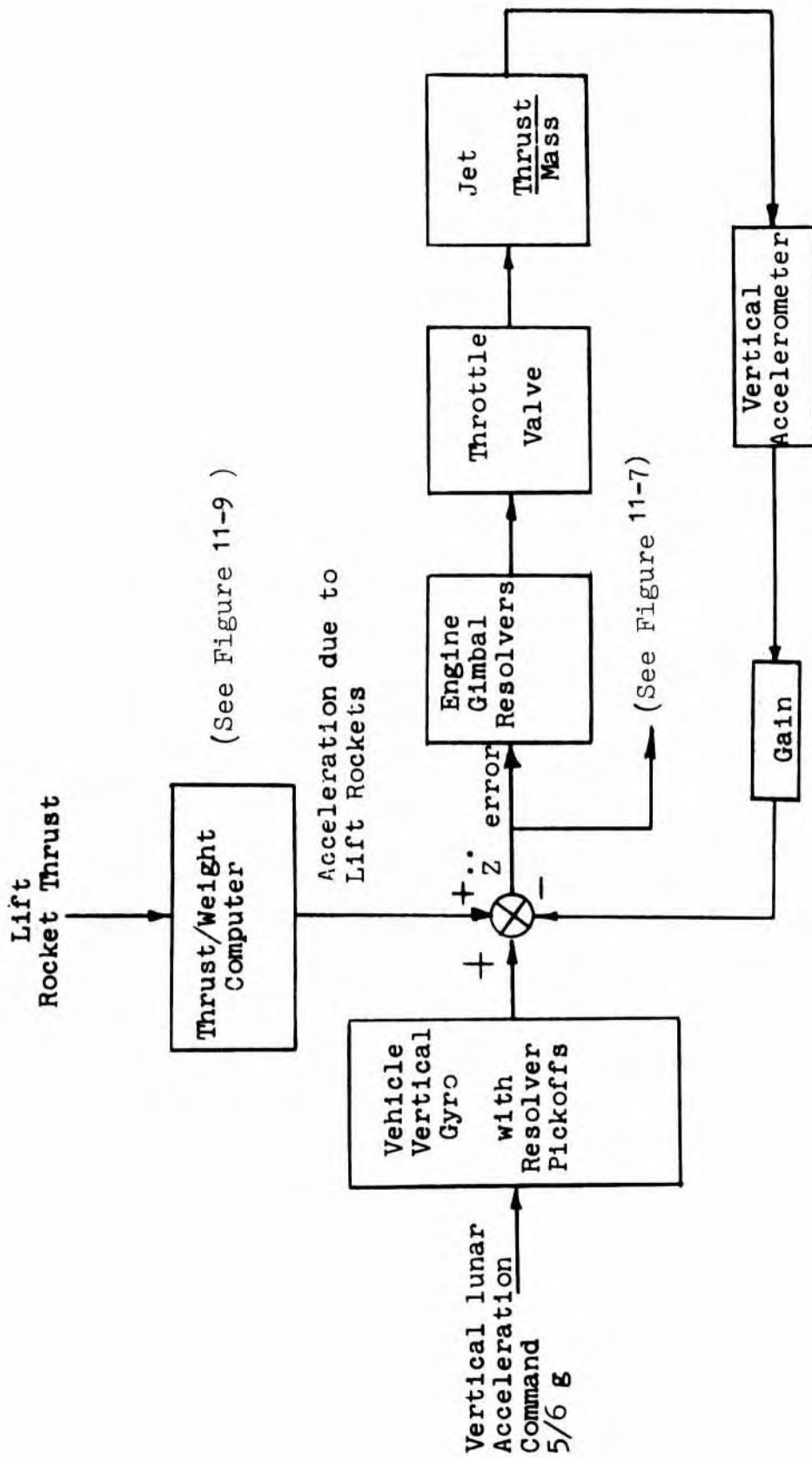


Figure 11-8. Automatic Jet Throttle Control System Block Diagram

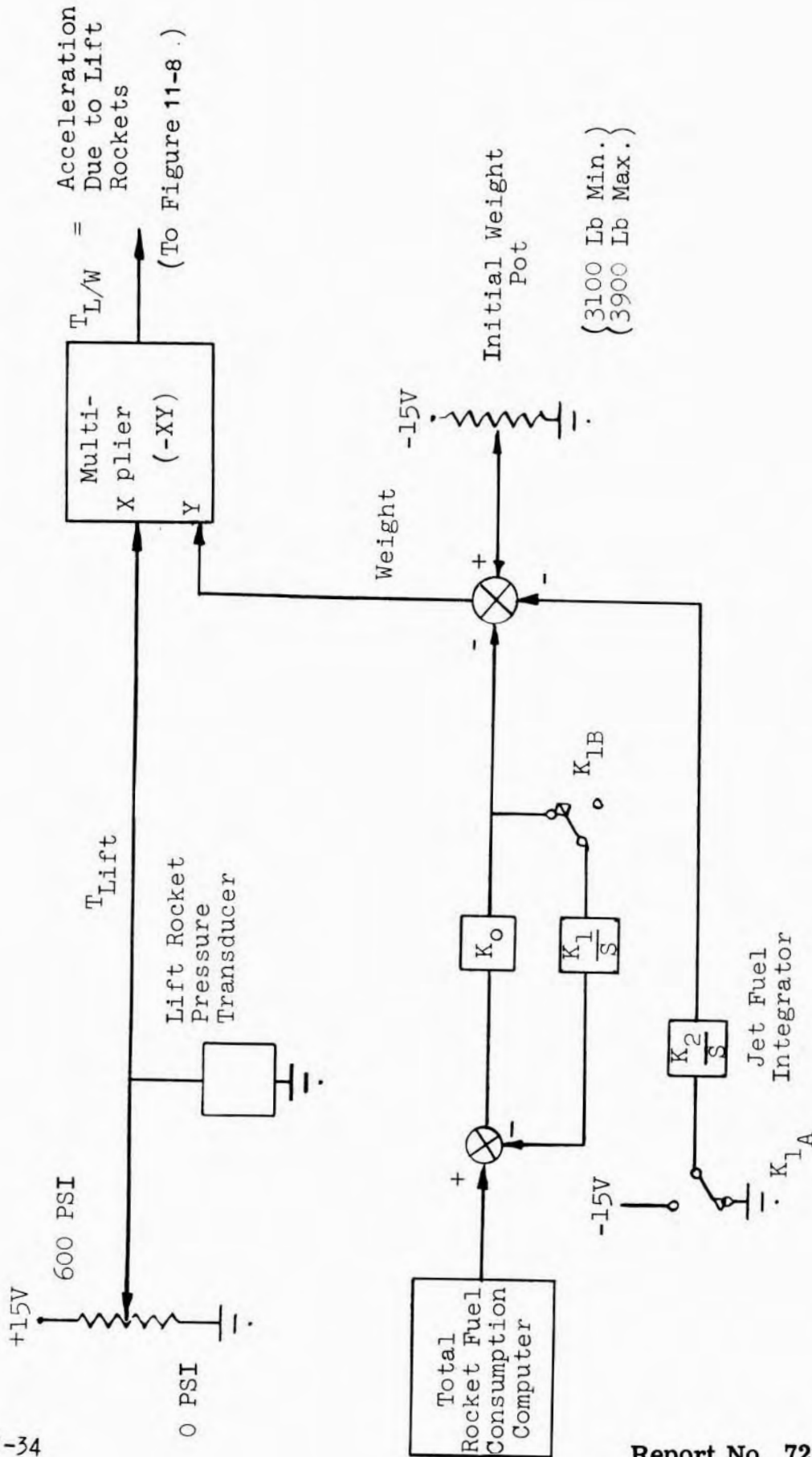


Figure 11-9. Thrust/Weight Computer

(figure 11-10) Gimbal Lock switch is in OFF position, a failure of hydraulic pressure automatically selects the emergency gimbal lock configuration. The action of the hydraulic pressure switch energizes K6 and applies positive 28 volts DC to the emergency gimbal lock solenoid and to the gimbal lock warning diode box. The 28 volts is diode coupled through this unit to the EMER GIMBALS LOCKED indicator on the annunciator panel, and to the master warning control box. When the emergency gimbal reset button is pressed, relay K6 is de-energized if the hydraulic low pressure switch has returned to normal. If there is a failure of primary DC or AC power or if the jet engine angle exceeds 15 degrees, the vehicle is automatically placed in Emergency Gimbal Locked configuration. This action is controlled by relays and the jet engine excess angle circuits in the Drag Compensation unit. With the gimbal lock switch OFF, positive 28 volts DC is routed through relays and diodes in the Drag Compensation unit, when a power failure or excess angle condition occurs, to the Gimbal Lock Warning diode box. This voltage is routed to the gimbal lock solenoid and through transistor switching action to the EMERGENCY GIMBALS LOCKED indicator. If the problem is that of excess angle, MAX ENGINE TILT indicator is also illuminated. The excess angle circuit computes the pitch and roll jet engine angle with respect to a local vertical reference, which is defined by the vertical gyro and energizes the emergency relay K10 whenever either pitch or roll angle exceeds 15 degrees. The gimbal potentiometers and gyro DC signals are summed and applied to a threshold bridge amplifier. Relay K19 enables a pressure switch in the normal gimbal lock hydraulic line when gimbal lock is selected by the pilot. If pressure in this line does not rise when mode is selected, K6 is energized and the emergency mode is selected.

11-60. LOCAL VERTICAL MODE

11-61. The Local Vertical mode aligns jet engine with the local vertical as sensed by the attitude gyros, regardless of vehicle outer frame motion.

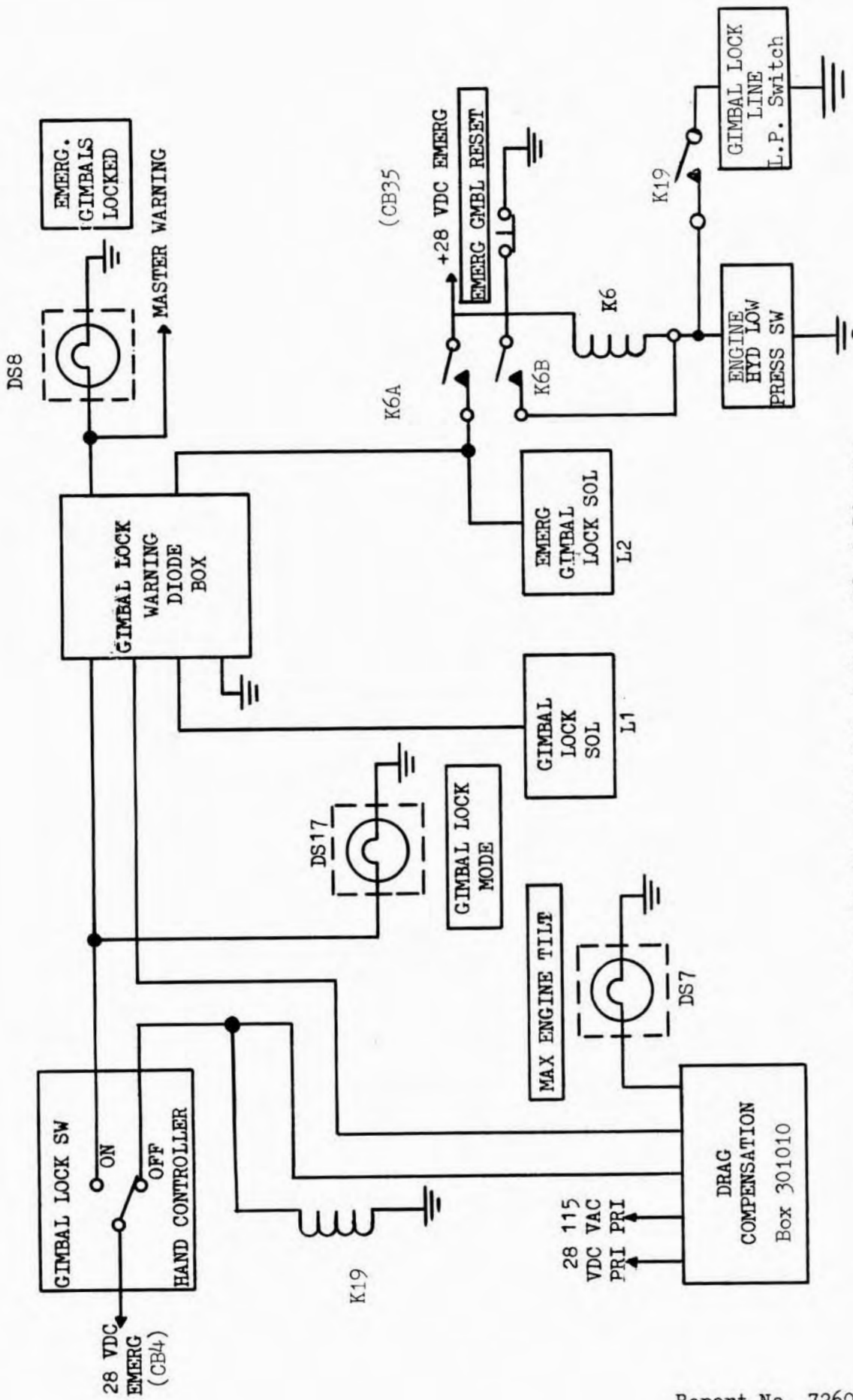


Figure 11-10. Gimbal Lock Mode, Block Diagram

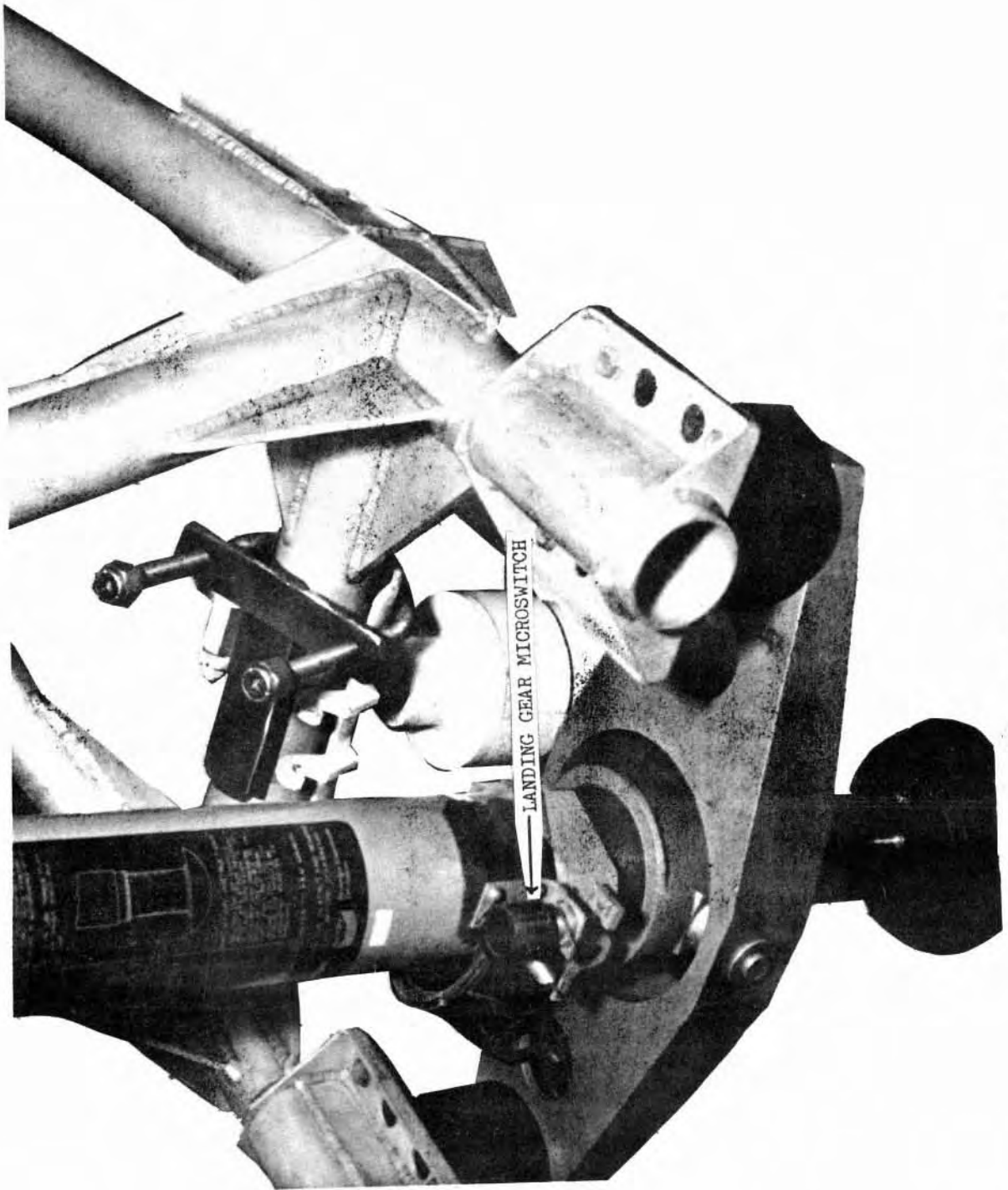


Figure 11-11. Typical Landing Gear Microswitch

The signal from the vehicle attitude gyro is compared with the engine gimbal angles obtained from potentiometers on the gimbal actuators. The resulting error is used as an input command to the gimbal actuator servo valves. The pilot may select this mode with a switch on the console.

This mode is automatically selected when:

- A. The vehicle is on the ground and any one of the four micro-switches located on each of the four shock struts (figure 11-11) indicates a compression of more than one-half inch, or
- B. The jet engine deviates more than 15 ± 1 degrees from the local vertical while in the Engine Centered or Lunar Simulation mode.
- C. When the Lunar Simulation Release button is depressed to manually disengage this mode, the pilot must momentarily activate the Local Vertical release switch on console, which places the jet engine attitude control in the Engine Centered mode if no other mode is selected.

11-62. LOCAL VERTICAL MODE BLOCK DIAGRAM ANALYSIS - The vertical gyro output from the attitude gyro unit is routed through the attitude gyro feedback circuit to the drag compensation unit. The outputs from the gimbal potentiometers (figure 11-5) are applied to the X-axis and Y-axis summing amplifiers and excess angle along struts circuits in the drag compensation unit (figure 11-50).

11-63. When Local Vertical is manually or automatically selected, relay K9 applies the vertical attitude signals to the summing amplifiers. The resultant output is routed through the de-energized contacts of the lunar sim relay to the compensation and integrator circuit and then to the actuator drive amplifiers. These amplifiers are current driving amplifiers capable of supplying a maximum of 5 milliamperes to the hydraulic

actuator servo valve coils. The roll and pitch actuators consist of two servo valve coils connected in series. A lead circuit is incorporated to compensate for delays in the jet stabilization loops which also drives the same coils.

11-64. The compensating network consists of two RC sections forming a low pass filter. The network serves as (1) a servo filter which maintains a low bandpass, and (2) a ripple filter for the 400-hertz half-wave demodulated signal from the gimbal resolver when operating in Lunar Simulation mode. The Integrator amplifier is used to ensure a low static error since the servo flow valve has a current deadzone. In other words, without an integrator a low DC offset could exist which would not be large enough to overcome the flow valve's current threshold and therefore a steady state engine position offset error would exist. A chopper stabilized low drift amplifier (Burr-Brown 2538A) is used as the integrator amplifier and ensures minimum integrating error.

11-65. The excess angle along the strut circuit computes the sum of the absolute pitch and roll gimbal angles and energizes relay K12 whenever this sum exceeds 64 degrees. The MAX ENGINE TILT indicator is illuminated when this occurs.

11-66. ENGINE CENTERED MODE

11-67. This mode is in operation when no other mode has been selected and the vehicle is airborne. This mode slaves the engine along the vertical vehicle body axis using the potentiometer signals on the gimbal actuators and the gimbal actuator servo valves used in all other modes except Gimbal Locked. With the exception, that the vertical gyro signals are removed from the X-axis and Y-axis summing amplifiers, the circuits in operation are the same as in local vertical operation.

11-68. JET STABILIZATION MODE

11-69. This jet engine attitude control mode performs as a portion of the Lunar Simulation system (refer to paragraph 11-70). During the Lunar Simulation mode, the drag compensation functions in the X and Y axes by positioning the jet engine to cancel aerodynamic drag. In the Z axis, the drag compensation is effected by automatically positioning the jet throttle to cancel aerodynamic drag and to compensate for vehicle changes in weight resulting from fuel burnoff. Refer to Thrust/Weight Computer, paragraph 11-75 for more detailed description of the Z-axis control.

11-70. LUNAR SIMULATION SYSTEM

11-71. The Lunar Simulation mode is comprised of: (1) drag compensation, and (2) thrust/weight control through the automatic jet engine throttle command of five-sixths of the vehicle weight. Drag compensation is similar to jet stabilization.

Lunar Simulation is effected in two steps:

- A. The automatic jet engine throttle system is activated with the jet engine in Gimbal Lock Mode; this results in jet engine thrust equal to five-sixths of vehicle weight, without any drag compensation.
- B. Unlocking the gimbal hydraulic system by positioning Gimbal Lock switch in the 3-axes attitude controller to OFF thus activating the drag compensation (jet stabilization) mechanism.

The Lunar Simulation System creates a psuedo lunar gravity field in which five-sixths of the vehicle weight is automatically supported by the jet engine and a pseudo lunar vacuum by automatically tilting and controlling the jet engine thrust to cancel aerodynamic drag on the vehicle. The system establishes a reference signal of $5/6$ g, which is

resolved into vehicle coordinates using a vertical gyro and gimbal resolvers. To this signal, acceleration caused by lift rockets (computered based on rocket thrust and vehicle weight) are vectorially added. The resulting acceleration information is compared with the measured vehicle accelerations obtained from body-mounted accelerometers. The resultant errors are used as command signals to the automatic throttle and jet engine attitude control, (figure 11-50). The effective weight of the vehicle is constantly changing, due to fuel consumption, thrust of the lift rocket, and engine attitude; therefore control of the jet thrust is provided by the automatic response of throttle electronic control circuits to the input data.

11-72. LUNAR SIMULATION BLOCK DIAGRAM ANALYSIS

11-73. The additional avionics stages in operation in this system are the thrust/weight computer, lift rocket electronics switch, accelerometers, body axis error or summing amplifiers, gimbal resolvers, booster amplifiers, error demodulators and the auto throttle circuits. In addition, the H_2O_2 remaining detector (computer) circuit, which provides a voltage to the H_2O_2 remaining indicator, provides required data to the thrust/weight computer (figure 11-50).

11-74. H_2O_2 REMAINING DETECTOR - This circuit computes the fuel consumed by the sixteen attitude rockets and the two lift rockets. This is accomplished by monitoring the output transistor of each rocket power amplifier and a lift rocket chamber pressure transducer, converting the ON signals to currents representing the burnoff rates and summing their currents in a chopper stabilized integrator amplifier. A T-resistor network is used to bias any OFF or quiescent drifts, and the H_2O_2 Set switch is used for adjustment of the integrator output and hence the H_2O_2 REM indicator reading. The integrator output is applied to a bias

and scale factor network to make it compatible with the cockpit fuel remaining indicator.

11-75. THRUST/WEIGHT COMPUTER - The computer calculates the vehicle acceleration along the Z body axis when the pilot actuates the lift throttle to engage the automatic throttle for the Lunar Simulation mode. The value of thrust/weight is continuously updated based on the integration of an assumed jet fuel flow rate, and the integration of the electronic rocket firing signals performed by the rocket fuel consumption detector circuitry (includes lift rocket fuel consumption). The two integrated signals are subtracted from the initial weight potentiometer signal (ground adjustable). This signal is then compared with one lift rocket pressure transducer signal (measure of lift rocket thrust) to obtain an instantaneous value of thrust/weight. This value is applied as one of the inputs to the Z-body axis error circuit.

11-76. LIFT ROCKET ELECTRONIC SWITCH - This circuit enables the auto throttle and thrust/weight computer when the lift rocket pressure exceeds a predetermined magnitude. The circuit operates by monitoring the 7.5 Kilohm lift rocket pressure transducer potentiometer with a comparator circuit whose output is at approximately negative 0.5VDC when the lift thrust is low and positive 10.5VDC when the thrust exceeds the trigger level. The amplifier output is applied to relay driver and energizes relays K11 and K18. Relay K11 contact enables the auto throttle motor driver's output stage and magnetic clutch. Relay K18 contacts latch in the relays and enable the Thrust/Weight computer to start computing the weight change due to fuel burnoff. The latch is necessary to ensure Lunar Simulation is not interrupted if the lift rocket pressure drops below the trigger point after start of Lunar Simulation. The relay driving voltage is derived from the Lunar Simulation switch and therefore will only operate after the Lunar Simulation switch has been put in the ON position.

11-77. VEHICLE AXIS ERROR AMPLIFIERS - The X-, Y-, and Z-axis error amplifiers perform a summing function. The Z-axis error has four inputs consisting of the computed thrust/weight value (T/W), the weight and drag vertical gyro resolver, and inputs from two accelerometers. The X- and Y-axis error amplifiers have only the latter three inputs.

11-78. The X-axis error amplifier sums the two X-axis linear accelerometer signals and the vertical gyro signal to generate an acceleration error signal with respect to the vehicle's X-body axis. During Lunar Simulation this error signal is used to position the X-axis thrust vector to compensate for drag along that axis. The X-accelerometer signals are summed together which compensates for rotational vehicle accelerations and allows for only linear, translational accelerations. The vertical gyro with resolver pickoffs has a 400-hertz output scaled for $5/6 g \sin \theta$. This signal is applied to a phase-sensitive demodulator and then filtered. The output of the error amplifier is scaled for $33.2 \frac{VDC}{g_e}$. The error amplifier signal is then modulated at 400-hertz and sent through a 400-hertz bandpass filter. The bandpass filter shapes the square wave signal to a 400-hertz sine wave output. It is necessary to change the DC error signal to an AC voltage in order to couple it through the gimbal resolvers.

11-79. The Y-axis error amplifier is very similar to the X-axis circuit. The only differences are in the gyro command signal and the ground test potentiometer feedback channel. The resolver gyro command is $5/6 g \cos \theta \sin \phi$ since roll is on the inner gimbal and requires one more resolution than pitch. The second difference is that the gimbal angle potentiometer is fed back to the inverting rather than the non-inverting input of the summing amplifier. This is necessary because the signal phasing in the engine channel differs in the pitch and roll axis.

11-80. The Z-axis error amplifier sums the two Z axis linear accelerometer signals, the vertical gyro signal and the $T_{L/W}$ computer (lift rocket acceleration) signal, and generates an acceleration error with respect to the vehicle's Z-body axis. During Lunar Simulation this error signal is used to adjust the Z-axis thrust to cancel $5/6$ of the earth's gravity and simulate a $1/6$ gravity field (lunar gravity). The Z accelerometer signals are summed together, which compensates for rotational vehicle accelerations, but allows only linear translational Z axis accelerations to be summed. The Vertical Gyro 400-hertz signal is scaled for $5/6 g \cos \theta \cos \phi$. This signal is applied to a phase-sensitive demodulator and then filtered. The output of the error amplifier is scaled for $33.2 \frac{VDC}{g_e}$. The error signal is modulated at 400-hertz, sent through a 400-hertz bandpass filter and applied to the gimbal resolvers.

11-81. THRUST/WEIGHT INDICATOR CIRCUIT - This circuit, consisting of a 2-stage amplifier, monitors the 2-axes accelerometers and provides an output to the telemetry and instrumentation system and drives the potentiometric $T_{L/W}$ indicator. Refer to section VIII for maintenance instructions on the indicator.

11-82. BOOSTER AMP AND RESOLUTION CIRCUIT - The booster amp and resolution circuit converts the three body axis acceleration error voltages to three jet engine axis acceleration error signals. The errors in the X and Y axis (\ddot{X}_{JE} and \ddot{Y}_{JE}) drive the pitch and roll jet stabilization systems respectively. The Z axis error (\ddot{Z}_{JE}) is coupled to the auto throttle control system to adjust the engine thrust magnitude. Four identical booster amps (two per package) are used as driving amplifiers for the temperature compensated gimbal resolvers. The transfer function of this resolver chain is on the following page.

$$\ddot{X}_{JE} = \ddot{X}_{BE} \cos \Theta + \ddot{Z}_{BE} \sin \Theta$$

$$\ddot{Z}_{JE} = \ddot{X}_{BE} \sin \Theta \cos \phi - \ddot{Y}_{BE} \sin \phi + \ddot{Z}_{BE} \cos \Theta \cos \phi$$

$$\ddot{Y}_{JE} = \ddot{X}_{BE} \sin \Theta \sin \phi + \ddot{Y}_{BE} \cos \phi - \ddot{Z}_{BE} \cos \Theta \sin \phi$$

The outputs of the X- and Y-axis stages are demodulated and routed by the contacts of the lunar sim relay K8 to the compensation and integrator stages, (refer to paragraph 11-64) and thus to the roll and pitch actuator drive amplifiers.

11-83. AUTO THROTTLE CHANNEL - The auto throttle channel provides a signal to drive the two-phase, 400-hertz rotary auto throttle actuator motor to the desired position. The channel has two modes of operation; (1) the Lunar Simulation Mode and (2) the Emergency Throttle Mode. In the Lunar Simulation Mode a Z-channel acceleration error is applied at the input and is fed to the auto throttle motor control phase with an AC gain of 3500. The output amplifier signal is coupled to the motor through the limit switch circuit relays during Lunar Simulation Mode. During Emergency Throttle operation relays K1 and K2 are energized, the throttle command synchro signal is applied through isolating resistors to the input amplifier and the auto throttle feedback synchro signal is applied through isolating resistors to the same amplifier. The remainder of the electronics used is the same as during Lunar Simulation, except relay contact K2A couples the output amplifier to the servo motor directly, therefore bypassing the limit switches.

11-84. AUTOMATIC THROTTLE LIMIT SWITCHES - Three microswitches limit the motion of the automatic throttle actuator such that the angular displacement of the jet throttle will not exceed the engine operating range during the Lunar Simulation Mode. These switches are preset as follows (degrees given refer to main fuel control shaft position on the jet engine):

- A. Maximum automatic throttle signal cutoff - 75°
- B. Low automatic throttle signal cutoff - 45°
- C. Low automatic throttle clutch disengage - 40°

The maximum and low cutoff switches (1 and 2) limit the motion of the automatic throttle actuator. The limits are based on sea level altitude and General Electric curves for CF700-2V engines. In the event of an excessive command by the auto throttle, the engine main fuel control will remain at the limited position until the lunar simulation commands the throttle position within the limits set. The low clutch disengage switch (3) acts as a backup to the low cutoff switch (2). When switch (3) has been activated, the pilot must take over manual control of the jet throttle. Switch (3) operates the LOW THRUST MANUAL indicator in the cockpit.

11-85. CIRCUIT ANALYSIS

11-86. The detailed circuit analysis is limited to a representative or typical circuit for each type of circuit when duplicated in primary, monitor, backup or drag compensation subsystems. Reference designators are for explanation only.

11-87. PRIMARY, MONITOR AND BACKUP ELECTRONICS

11-88. Circuit analysis is presented in an operational sequence of the following circuits: rate command, rate model, direct model, model lead, rate gyro feedback (circuit similar to rate command), attitude gyro feedback, attitude hold and synchronizer, yaw attitude gyro feedback, yaw attitude hold and synchronizer, threshold amplifier and inverter, rocket inhibit logic and rocket amplifiers. Special monitoring circuits and jet engine attitude control circuits are subsequently discussed.

11-89. RATE COMMAND CIRCUIT - The 800-hertz AC signal from the hand controller is applied across the gain adjust potentiometer, (figure 11-12). The overall gain from the potentiometer slider to the final amplifier output is nominally 4.54 vdc/vrms. The potentiometer is normally set to approximately 78% of its full range, leaving the remainder to compensate for hand controller scale factor or circuitry gain change. After amplification, the signal is demodulated and filtered. The filter attenuates the signal by approximately 67 decibels, which results in a ripple less than 4 millivolts RMS at maximum command. A 22-turn adjustment potentiometer is used for nulling hand controller or demodulator offsets. Refer to paragraph 11-149 for adjustment procedures. Refer to paragraph 11-20 for description of attitude control mode selection. In the Rate with Model mode the output of the rate command final amplifier is applied through the appropriate relay contacts (primary and monitor attitude channels) to the rate model input differential amplifier (figure 11-13) and the coupling diodes input of the rate model lead circuit (figure 11-15).

11-90. RATE MODEL CIRCUIT - The rate model circuit (figure 11-13) operation can be analyzed by reference to the typical signal traces (figure 11-14). Assume the model rate, TP-C and stick command rate are both zero, and then a step rate command of 10^0 /sec from the stick is created. This causes amplifier, A1 output to limit, creating approximately 10.5 VDC at TP-A, and the top of the 22 turn model acceleration adjustment potentiometer. Assume an 8 DEG/SEC² acceleration is desired, then approximately 6 VDC will be applied to the model integrator, A2, input resistors, TP-B. Since the model rate signal is different than the command by more than one degree per second, relay K2 will be energized and the input resistors will be paralleled (4-jet logic). The model output signal, TP-C will increase at a rate of 4 volts per second (8 DEG/SEC²) until time, T_1 , when the model rate is within a degree per second of the stick command signal. At this time, relay K2 will

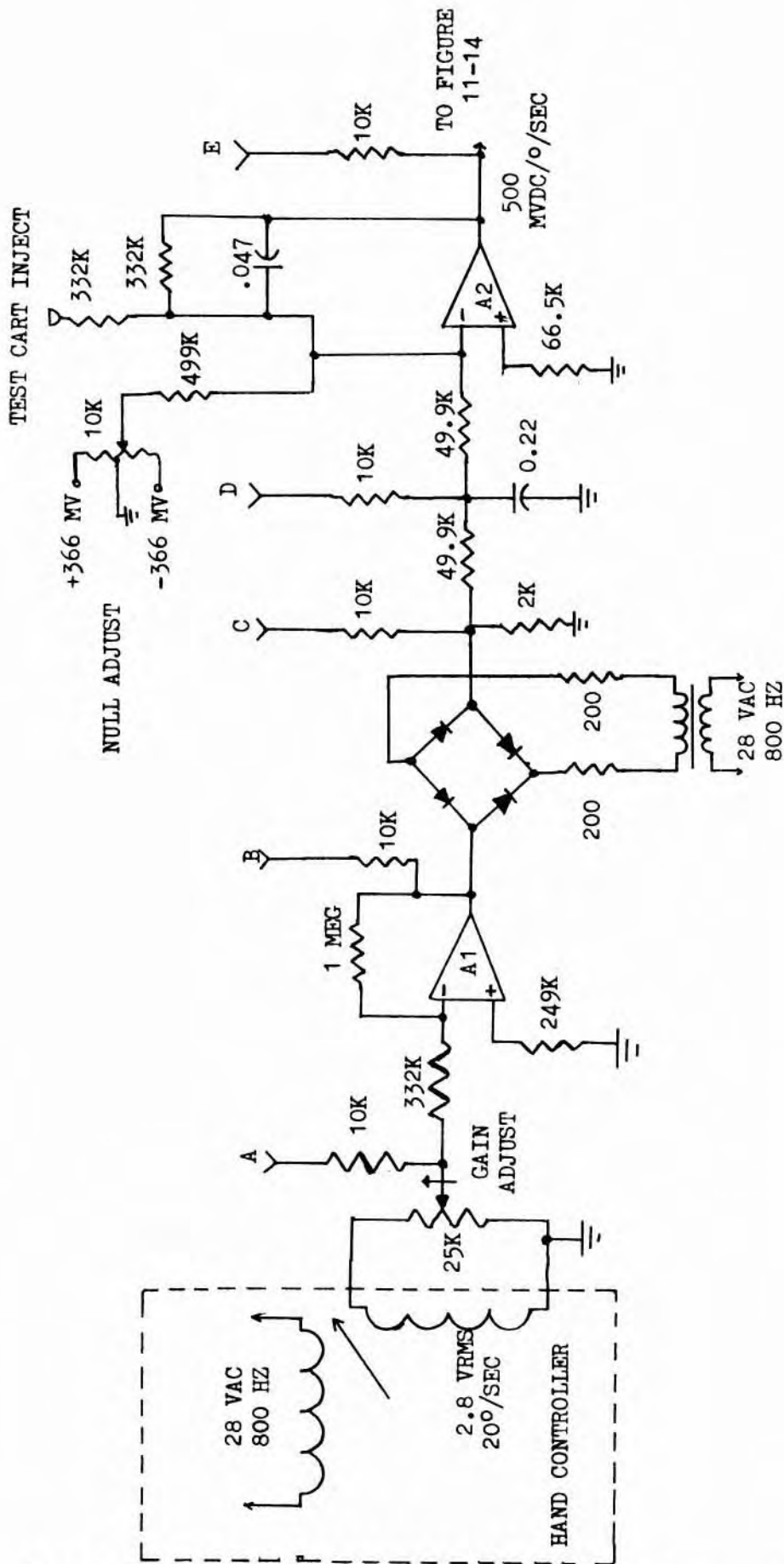


Figure 11-12. Rate Command Circuit, Schematic Diagram

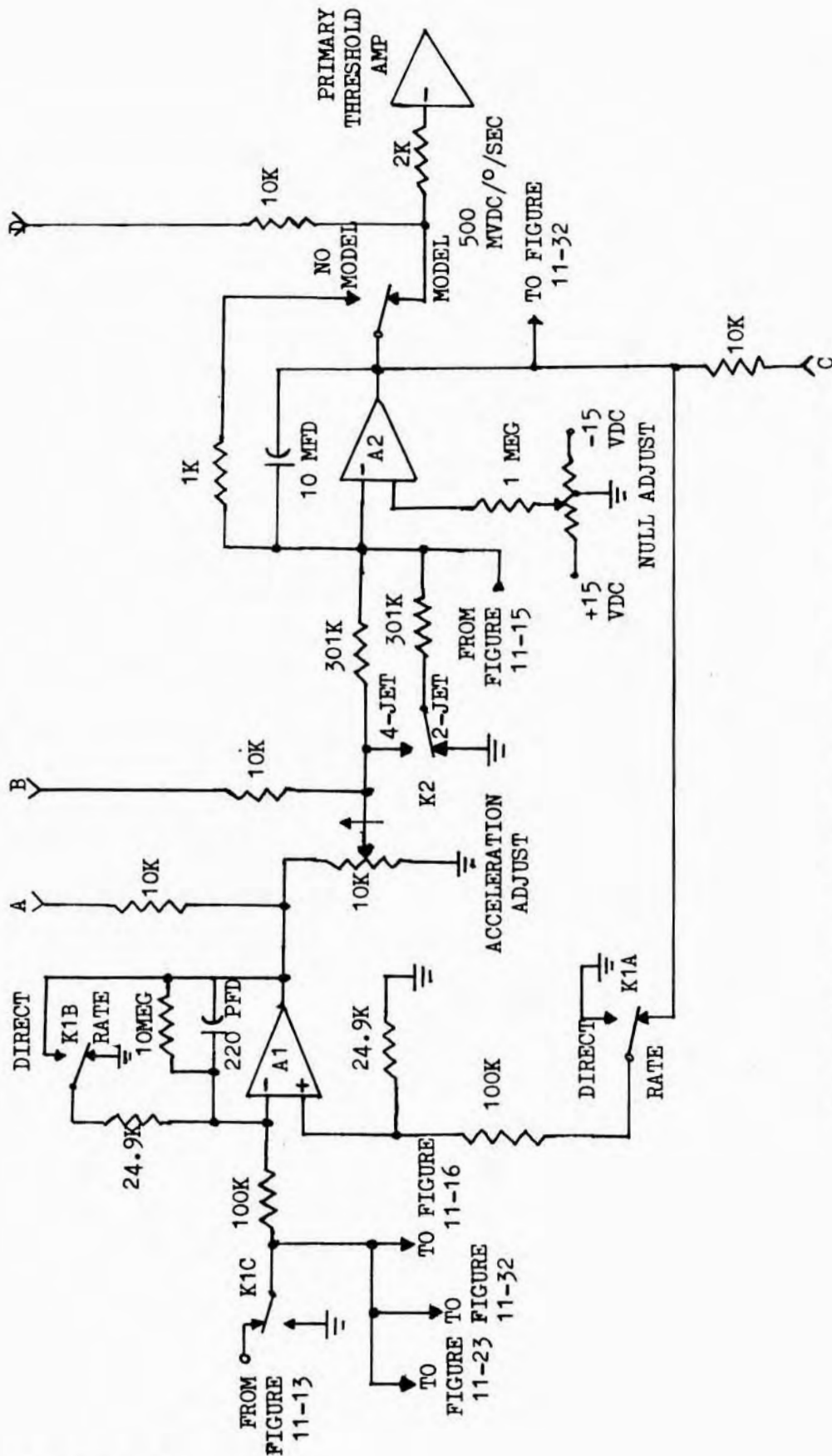


Figure 11-13. Rate Model Circuit, Schematic Diagram

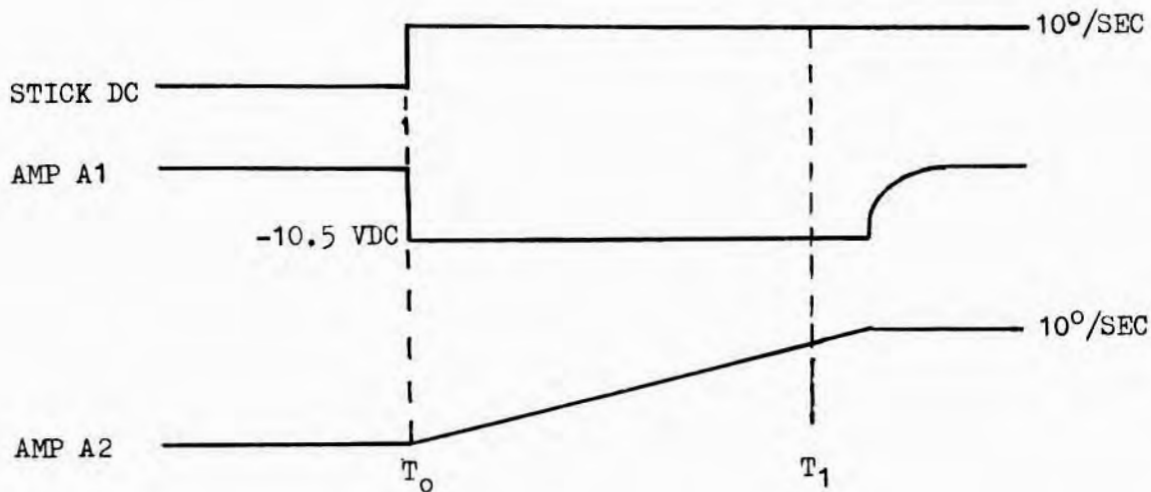


Figure 11-14. Rate Model Typical Signal Traces

de-energize and the model output will continue to increase at a rate of 2 volts per second (4 DEG/SEC^2) until the model output is equal to the stick command signal. The model output will then remain equal to the commanded rate until the command is changed. Relays K1 and K3 are Rate/Direct and Model/No Model mode switching relays respectively. Relay K3 contact keeps the integrator at a low (0.003) gain during No Model mode so that a large model command signal is not present when switching to Model mode. If in Direct with Model operation, relay K1 is energized and the input to the rate model final amplifier A2 is from the direct model circuit.

11-91. DIRECT MODEL CIRCUIT - The direct model circuit (figure 11-15) receives input signals from the direct switches to the same amplifier used in the rate model circuit, however, it is the only amplifier stage. Whenever the pilot moves the hand controller enough to close a functional direct switch, S1 or S2, approximately 14 volts DC is applied at TP-A if relay K1 is energized (Direct Mode selected). This provides

approximately 9.3 volts DC across the 22 turn acceleration adjustment potentiometer. Assume 8 deg/sec^2 acceleration is desired, then approximately 4.8 volts DC would be present at the potentiometer arm as an input signal to the open loop integrator. The model amplifier capacitor will charge linearly at 4 volts DC/sec (8 deg/sec^2) until the hand controller is returned to the detent position, and the voltage at TP-A goes to zero or the amplifier limit (10.5 volts DC) is reached. Resetting of the model can be accomplished by switching to No-Model mode and allowing relay contact, K3D, to discharge the 10 microfarad storage capacitor. Since the output of the integrator represents the rate command to the vehicle in that axis, the vehicle rate at the time that the hand controller switches disengage, will be maintained until a function command is received from the hand controller. However, if this vehicle rate is less than $3^\circ/\text{second}$, the attitude hold system will maintain the vehicle attitude. In yaw, there is no attitude hold in the Primary Direct Command mode.

11-92. MODEL LEAD CIRCUIT - When in the rate model configuration, there would be a lag between pilot's command and rocket firing. This requires the addition of a model lead circuit (figure 11-16) to compensate for this lag time. This lag time is nominally equal to the rate threshold setting divided by the selected model acceleration. For a 1.4 deg/sec threshold and an 8 deg/sec^2 model acceleration the time lag would therefore be 175 milliseconds. Whereas, for a maximum rate threshold of 2.0 deg/sec and a minimum model acceleration of 4 deg/sec^2 , the lag time would be 0.5 second; this large a lag time could easily be noticed by the pilot and give an undesirable system operation. The lead term can provide a short duration initial rocket pulse as soon as the pilot moves the hand controller and, therefore, give the pilot a feeling of immediate system response. The circuit operation is as follows: when the hand controller is moved and provides an output beyond approximately 1.4 deg/sec amplifier A1 becomes saturated and provides a ten-volt step

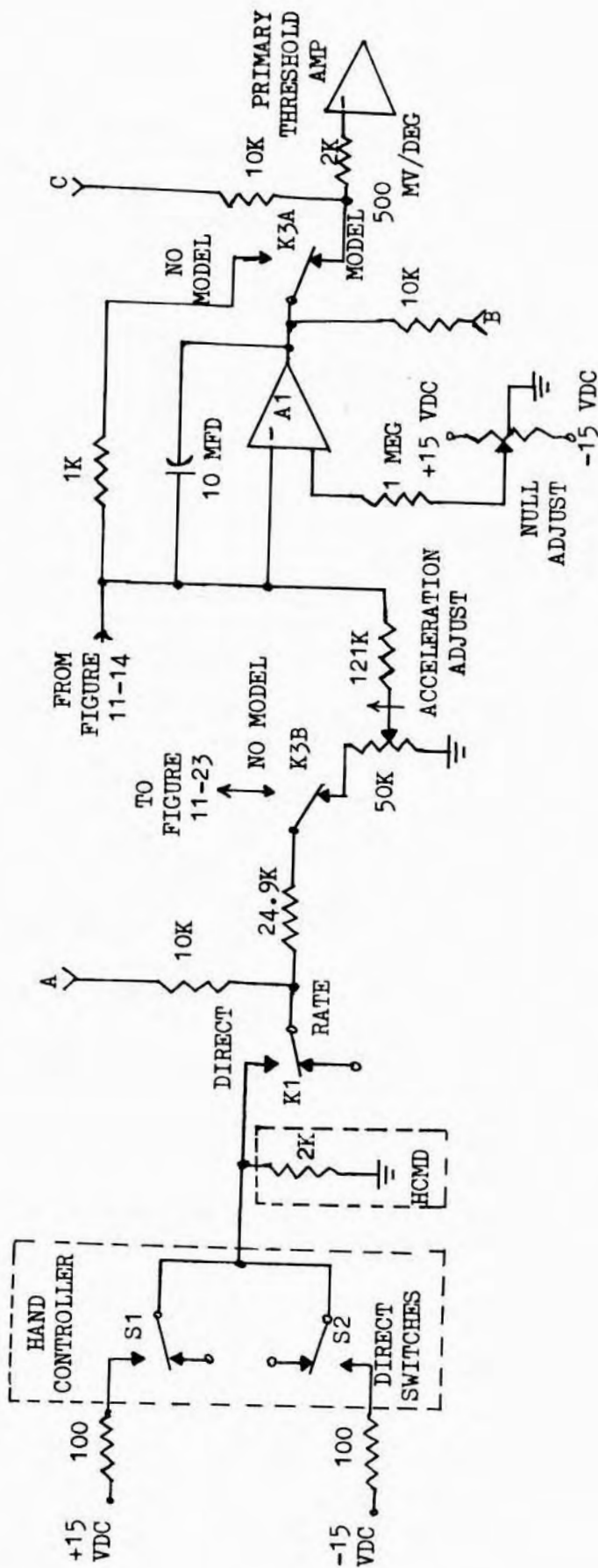


Figure 11-15. Direct Model Circuit, Schematic Diagram

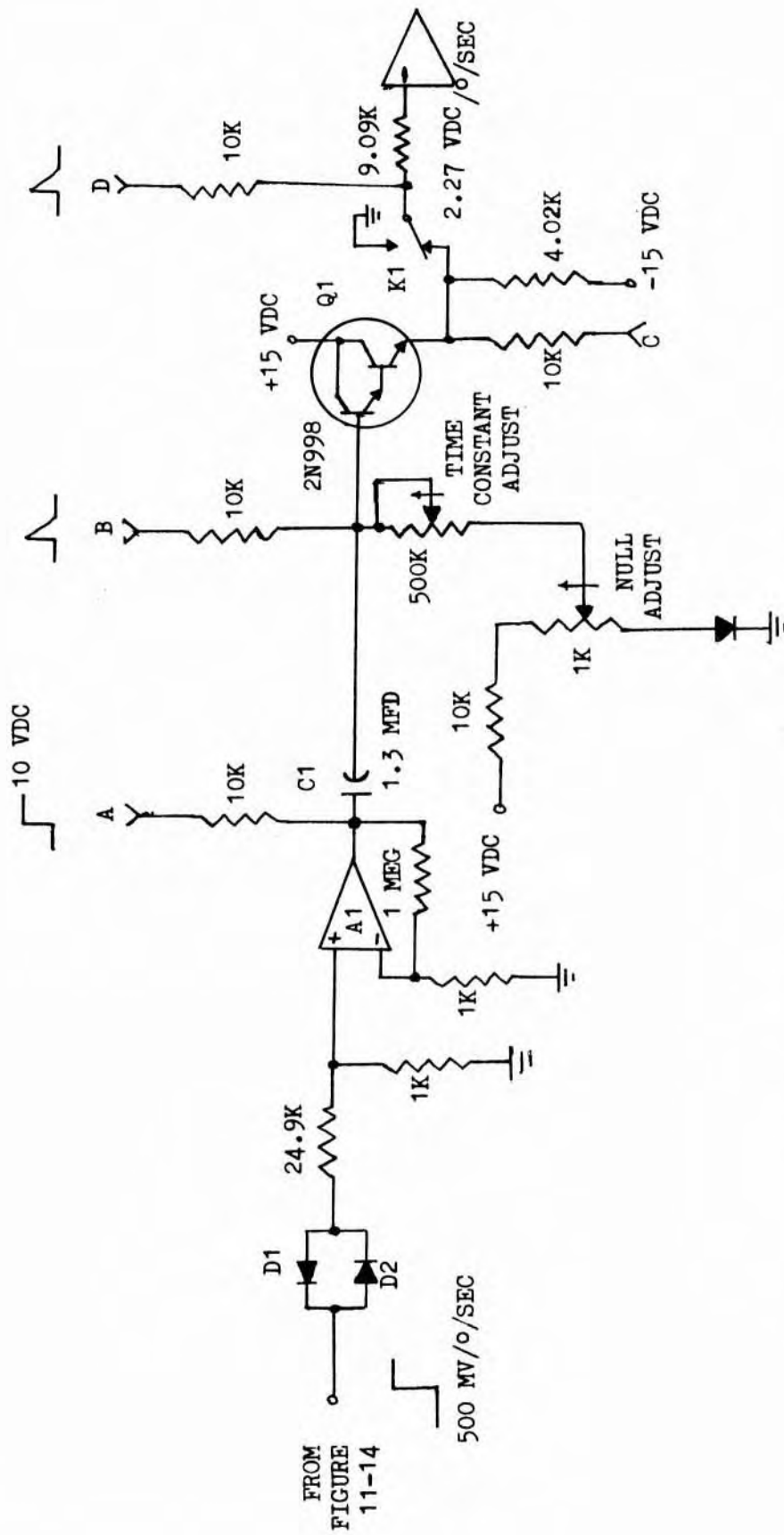


Figure 11-16. Model Lead Circuit, Schematic Diagram

voltage to the uncharged capacitor, C1 (TP-A). The RC network creates a ten-volt peak pulse at TP-B. This pulse is applied to a Darlington emitter follower amplifier, serving as a buffer, which overcomes the rate threshold and generates a rocket firing command. The threshold amplifier will remain on until the pulse voltage decays below the threshold value, thus the duration of the initial rocket firing is controlled by the setting of the time constant adjustment potentiometer. The high gain (40) amplifier A1 allows the shape of the lead pulse to be independent of the amount of hand controller command, since any amount of stick command which is larger than 1.4 deg/sec will saturate amplifier A1. Diodes D1 and D2 provide a deadzone area in order to prevent creating spurious pulses due to stick noise or offsets. A null adjustment potentiometer is included to allow nulling the lead circuits DC offset at TP-C.

11-93. The rate gyro and attitude gyro outputs also feed a signal to the threshold amplifier circuits, thus these stages are discussed prior to the threshold amplifier circuit.

11-94. RATE GYRO FEEDBACK CIRCUIT - The rate gyro feedback circuit (figure 11-17) is very similar to the rate command circuit, however, the initial input amplifier is not required. The input from the rate gyro synchro is applied across a 22-turn gain potentiometer which is normally set to approximately 88% of its full range, leaving the remainder to compensate for rate gyro scale factor or circuitry gain change. The overall gain from the potentiometer arm (TP-A) to amplifier A1 output (TP-D) is nominally 3.85 vdc/vrms. A half-wave, phase sensitive demodulator determines the feedback signal polarity and applies it to the filter network, as a half-wave, rectified 400-hertz signal. The demodulator filter consists of two RC sections which provide approximately 52 decibels attenuation at the 400-hertz demodulator filter frequency, and therefore at maximum feedback (10 vdc), the

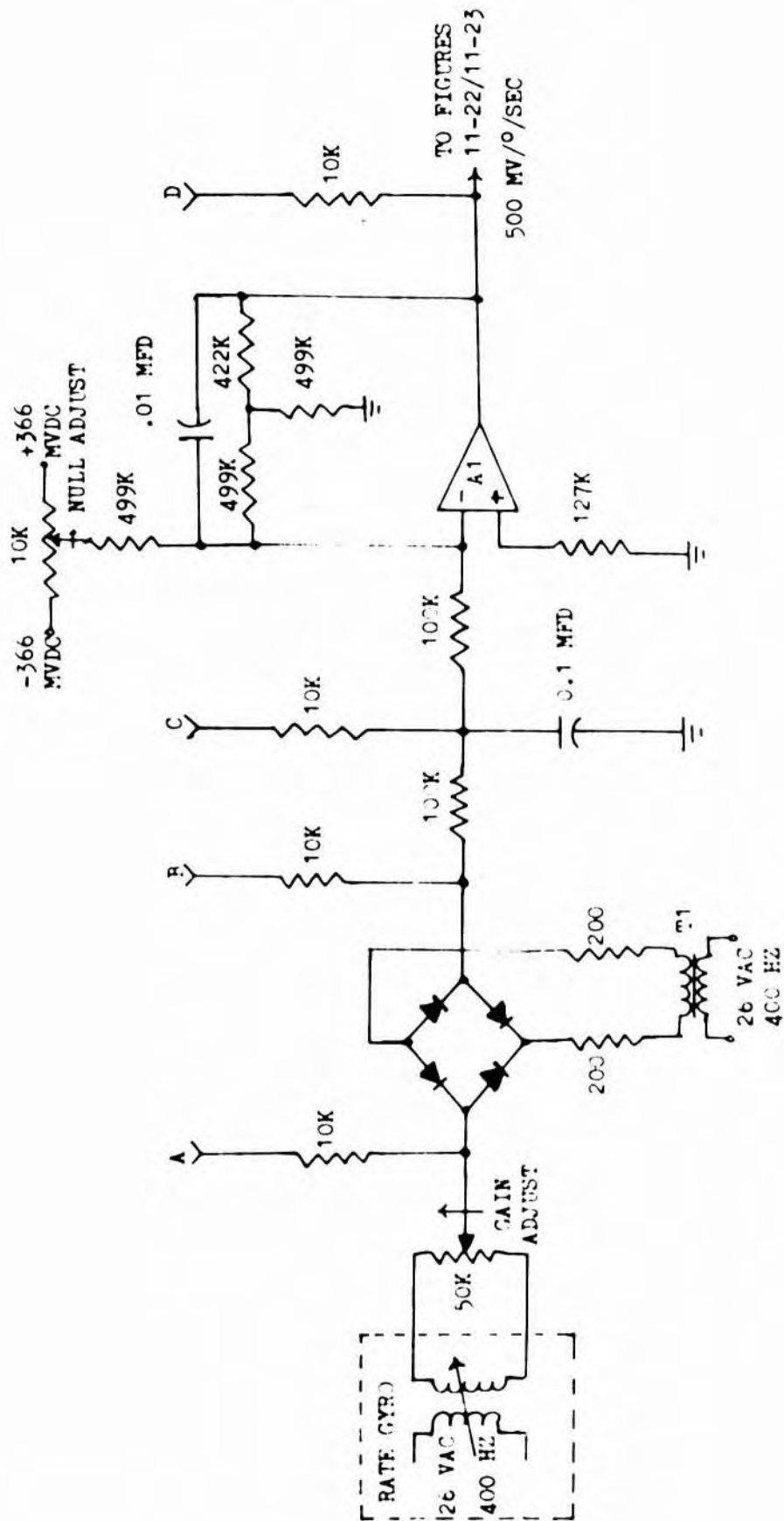


Figure 11-17. Rate Gyro Feedback Circuit, Schematic Diagram

output ripple is less than 20 millivolts RMS. A 22-turn adjustment potentiometer is used for nulling rate gyro or demodulator offsets and is capable of adjusting for maximum offsets of 980 millivolts DC. The output is routed to the threshold amplifier circuit (figure 11-23).

11-95. ATTITUDE GYRO FEEDBACK CIRCUIT - The pitch attitude gyro feedback circuit and the roll attitude gyro circuit (figure 11-18) are identical feedback circuits but differ slightly from the yaw attitude gyro feedback circuit, (figure 11-20). The vertical gyro signal from the attitude gyro unit is applied to the 3-axes ball in the attitude indicator and to the input potentiometer of the feedback circuit. The 22-turn gain adjustment potentiometer is normally set to approximately 71% of its full range, leaving the remainder to compensate for attitude gyro scale factor or circuitry gain changes. The overall gain from the gain potentiometer arm (TP-A) to amplifier A1 output (TP-D) is nominally 1.41 vdc/vrms. A half-wave, phase sensitive demodulator determines the feedback signal polarity and applies it to the filter network as a half-wave, rectified 400-hertz signal. The demodulator filter consists of two RC sections which give approximately a 57 decibel attenuation at the 400-hertz demodulator filter frequency, and therefore at maximum feedback the output ripple is less than fifteen millivolts RMS. A 22-turn adjustment potentiometer is used for nulling attitude gyro or demodulator offsets, and is capable of adjusting over the full amplifier range. The output signal is applied to the Drag Compensation unit for use in the jet engine attitude control circuits and to the attitude hold and synchronizer circuits in pitch and roll channels.

11-96. ATTITUDE HOLD AND SYNCHRONIZER CIRCUIT - The attitude hold and synchronizer circuit (figure 11-19) performs the following functions: (1) maintains an attitude reference and computes the vehicle attitude error during attitude hold (no pilot command) periods, (2) updates the

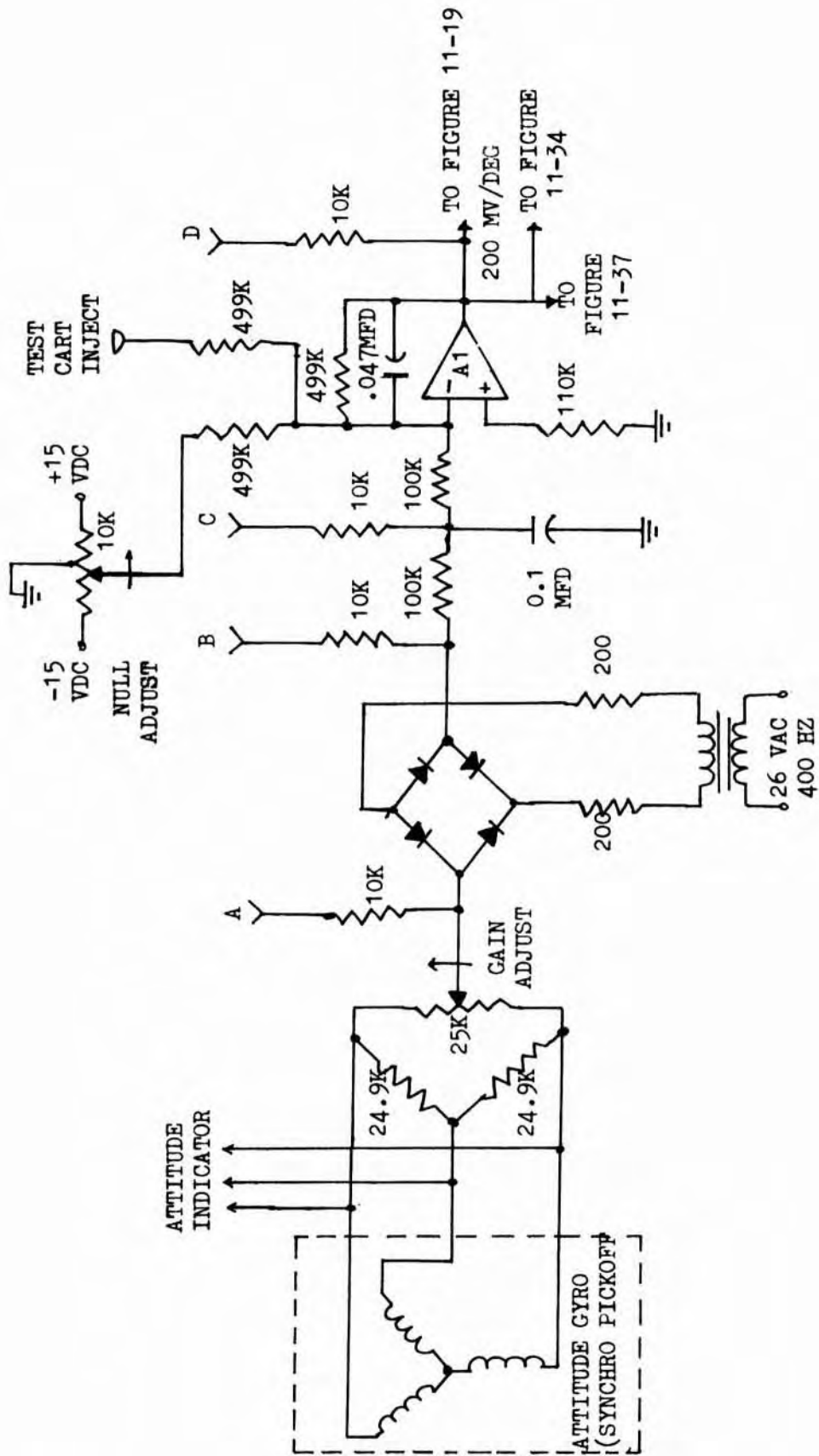


Figure 11-18. Pitch and Roll Attitude Gyro Feedback Circuit, Schematic Diagram

attitude reference during a commanded maneuver, and (3) establishes the ratio of rate to attitude error feedback signal which controls the attitude rocket firing commands. The first function is accomplished by storing an attitude reference voltage on the integrator amplifier, A2, output TP-C and comparing the signal to the total attitude signal in difference amplifier, A1. The difference amplifier with a DC gain of 25.3 has an output scale factor of 5 vdc/deg at TP-A. During an attitude hold period, the chopper stabilized integrator amplifier, A2, with a high quality Mylar storage capacitor, keeps the reference drift less than 0.05 deg/min over the entire operating temperature range of zero to 140°F.

11-97. Updating the attitude reference is accomplished by energizing relay K1 and closing the feedback loop. This forces the integrator amplifier, A2, output to follow the total attitude signal, since if a difference exists it creates a large output from amplifier, A1, that is applied through relay contact K1A to the integrator input and drives the amplifier to the correct value. The integrator output slewing rate for a ten volt attitude error signal is approximately 25 volts per second (125 degrees per second) and is quite sufficient for the maximum expected vehicle rates of 22 degrees per second. During maneuvering, relay contacts K1B and K2A ground the signals to the threshold amplifiers, thus preventing the attitude error from influencing the rocket commands. The amount of attitude error to rate signal ratio is controlled by a 22-turn adjustment potentiometer capable of adjusting for 0.3 to 1.5 degrees attitude threshold when the rate threshold is fixed at any value from 0.5 to 2.0 degrees per second. This gives a RATE/ATT ratio of 0.33 to 6.7. The attitude hold and synchronizer circuit output is applied to the primary threshold amplifier circuit (figure 11-23) and the threshold amplifier stages in the monitor channel. The same output is also available to drive the attitude indicator needle circuit, but this

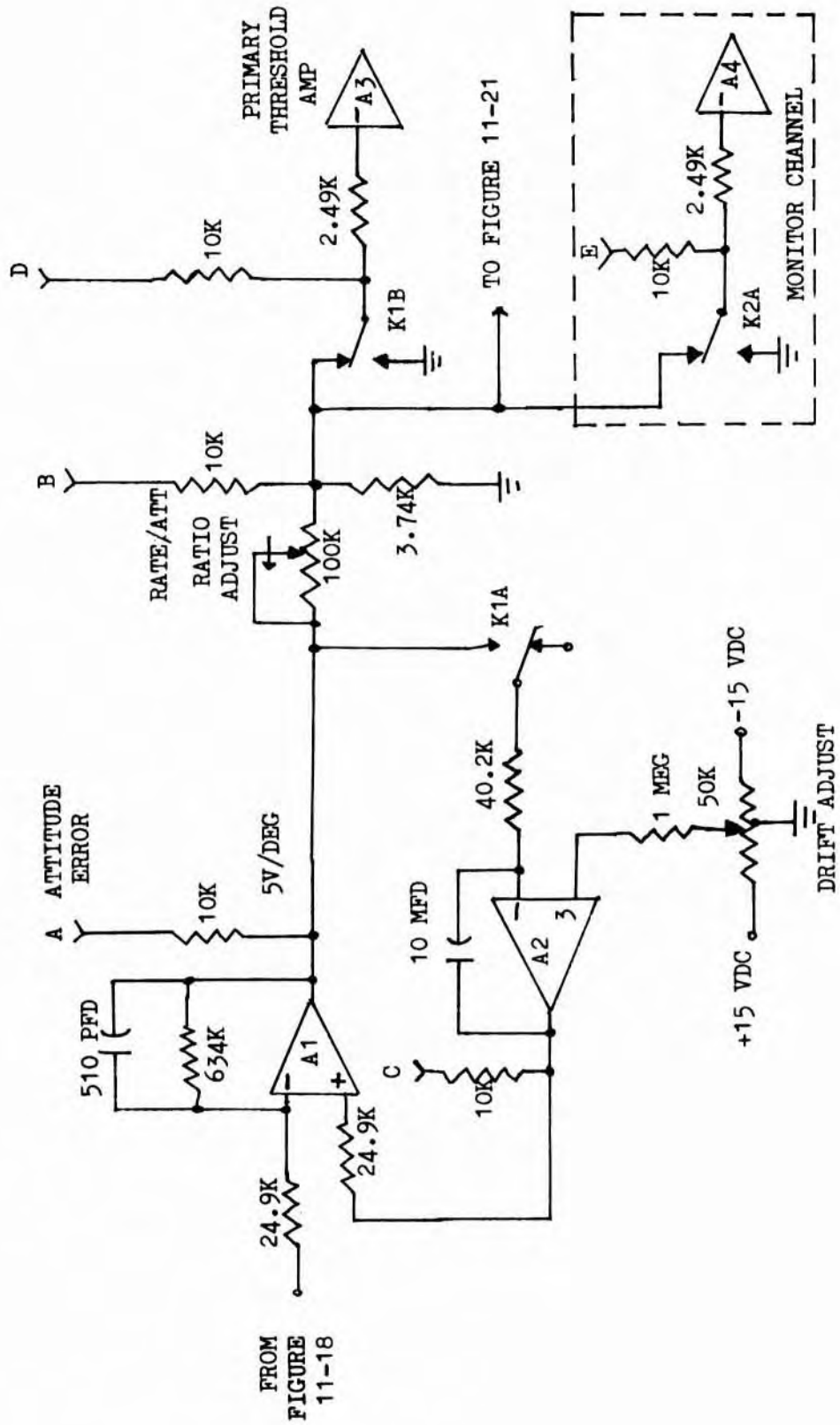


Figure 11-19. Attitude Hold and Synchronizer Circuit, Schematic Diagram

output is not used (figure 11-21). In pitch and roll, attitude hold is returned in the primary direct command mode. On yaw attitude, hold is disconnected in the primary direct command mode.

11-98. YAW ATTITUDE GYRO FEEDBACK CIRCUIT - The yaw attitude gyro (directional gyro) feedback circuit (figure 11-20) is used primarily for instrumentation, and does not feedback a signal to control rocket firings or attitude hold as does the pitch and roll attitude gyro. The directional gyro signal is applied to a Control Differential Transformer (CDX), in the cockpit, which allows the pilot to set the desired heading on the attitude indicator. The output of the CDX is applied to the 22-turn gain adjustment potentiometer which is normally set to approximately 57% of its full range, leaving the remainder for gyro scale factor or circuitry changes. The output signal from the CDX has a maximum value of 11.9 vrms (attitude ball at East or West). The overall gain from the gain potentiometer's arm (TP-A) to amplifier A1 output (TP-D) is nominally 1.56 vdc/vrms. A half-wave phase sensitive demodulator determines the feedback signal polarity and applies it to the filter network as a half-wave rectified 400-hertz signal. The demodulator filter consists of two RC sections which gives approximately a 43 decibel attenuation at the 400-hertz demodulator filter frequency, and therefore, at maximum signal of 10 vdc the output ripple is less than 60 millivolts RMS. A 22-turn adjustment potentiometer is used for nulling the directional gyro or demodulator offsets and is capable of adjusting over the full output voltage range. The output signal is applied to the yaw attitude needle circuit, when used (figure 11-21).

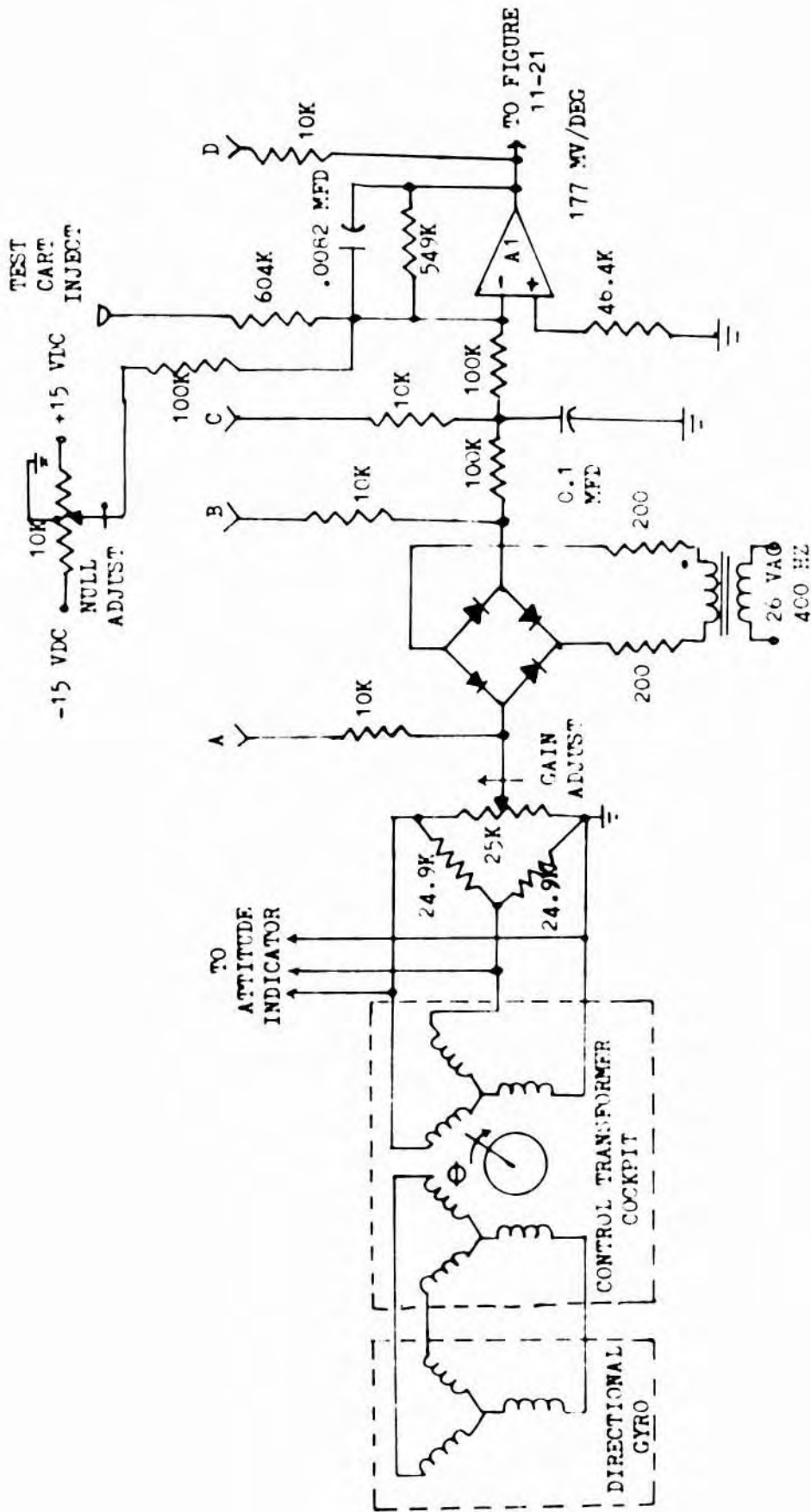


Figure 11-20. Yaw Attitude Gyro Feedback Circuit, Schematic Diagram

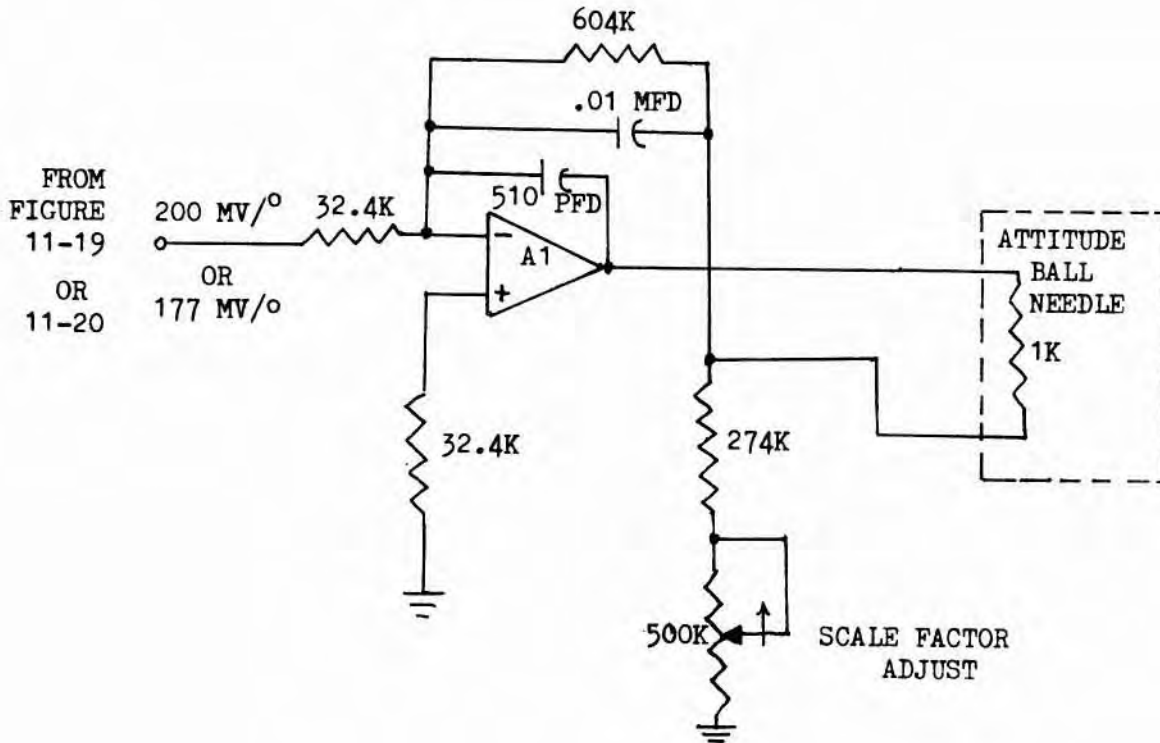


Figure 11-21. Attitude Needle Circuit, Schematic Diagram

11-99. YAW ATTITUDE HOLD AND SYNCHRONIZER CIRCUIT - The attitude hold and synchronizer circuit (figure 11-22) has the following functions: (1) computes the vehicle attitude error during attitude hold periods (no pilot commands), (2) resets the attitude error to zero during a commanded maneuver, and establishes the ratio of rate to attitude error feedback signal which controls the attitude rocket firing commands. The first function is accomplished by applying the yaw DC rate gyro feedback signal to integrator amplifier A1. Over a fixed time interval, the amplifier's feedback capacitor will accumulate a voltage representing the attitude error with a scale factor of 5 volts DC/deg. If the yaw rate is zero, the integrator is capable of holding the attitude error with less than 0.05 deg/min drift over the temperature range of zero to

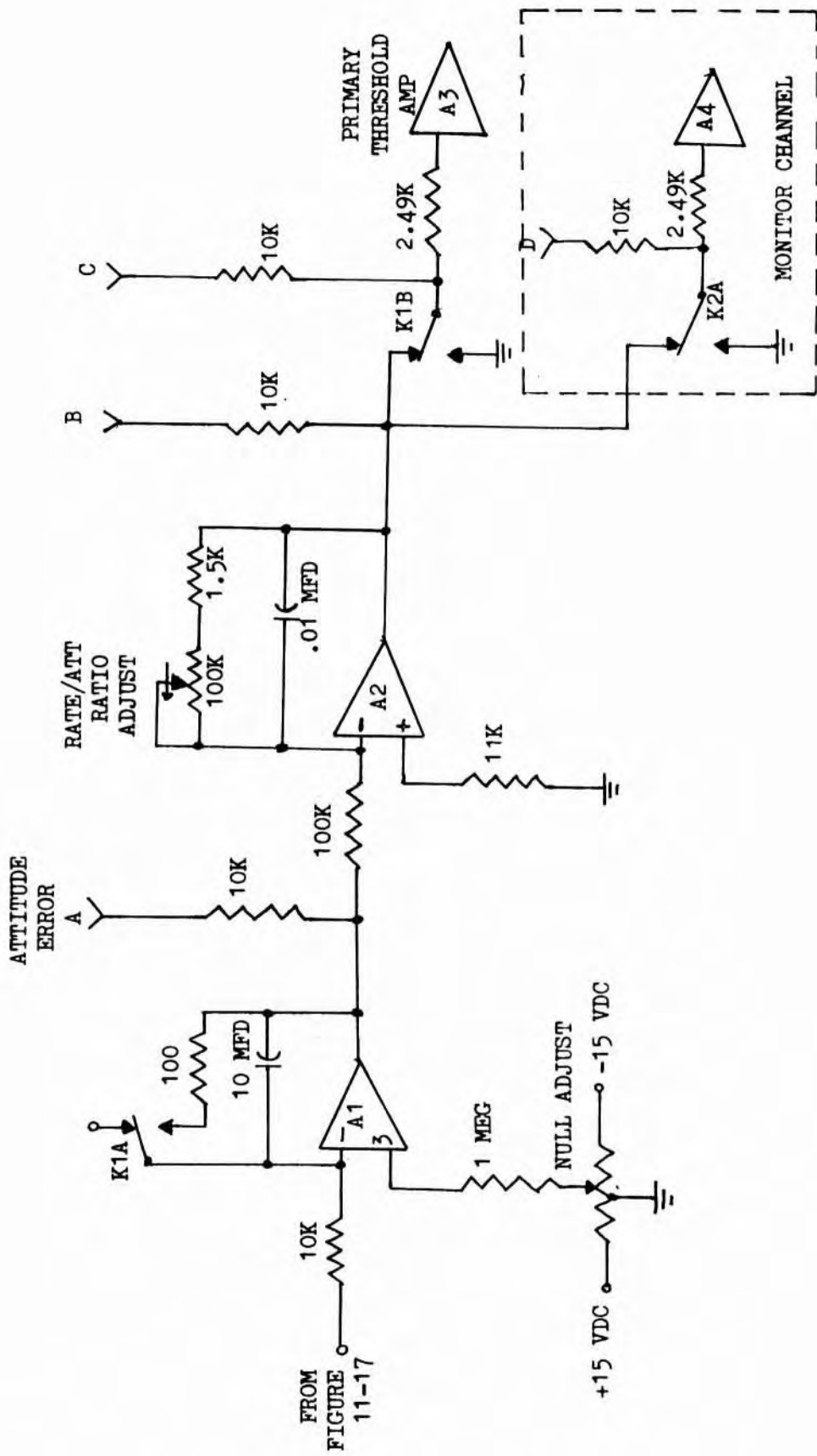


Figure 11-22. Yaw Attitude Hold and Synchronizer Circuit, Schematic Diagram

140°F. However, in practice, the yaw rate gyro signal possesses some offset voltage, caused by a combination of rate gyro null shift, hysteresis, and striction which causes attitude error signal drift much greater than the integrator and electronic circuit drift. Typical rate gyro offset voltages are in the range of 20 to 80 millivolts DC, which results in 2.4 to 9.6 deg/min attitude error drift. During maneuvering relay contact K1A establishes a low gain (0.01) for amplifier A1 and discharges the 10 microfarad attitude error storage capacitor, thereby resetting the attitude error to zero. Relay contacts K1B and K2A ground the signals to the threshold amplifiers, thus preventing the attitude error from influencing the rocket firing commands. The amount of attitude error to rate signal ratio is controlled by a 22-turn adjustment potentiometer capable of adjusting for 0.3 to 1.5 degrees of attitude threshold when the rate threshold is fixed at any value from 0.5 to 2.0 degrees per second. This gives a rate/att ratio of 0.33 to 6.7. The output of the yaw attitude hold and synchronizer circuit drives the threshold amplifier circuits (figure 11-23) in the primary and in the monitor channels.

11-100. THRESHOLD AMPLIFIER AND INVERTER CIRCUIT - The threshold amplifier (figure 11-23) employs a feedback diode bridge network which operates as follows: with all input signals zero, all bridge diodes D1 through D4 are forward biased therefore keeping the amplifier output at zero volts. The forward biased diodes effectively provide a very low feedback impedance which creates an extremely low gain. The T-resistance networks provide a fixed current to the diodes which can be set by adjustment potentiometers. Assume an input signal is now increased positively. This will create a current, I_o , to unbalance the currents in the bridge diodes such that the current in D3 would increase by I_o and the current in D4 would decrease by the same amount, since a constant current is maintained through the 10 kilohm resistor, R2. Eventually, the current I_o will become equal to the fixed current through

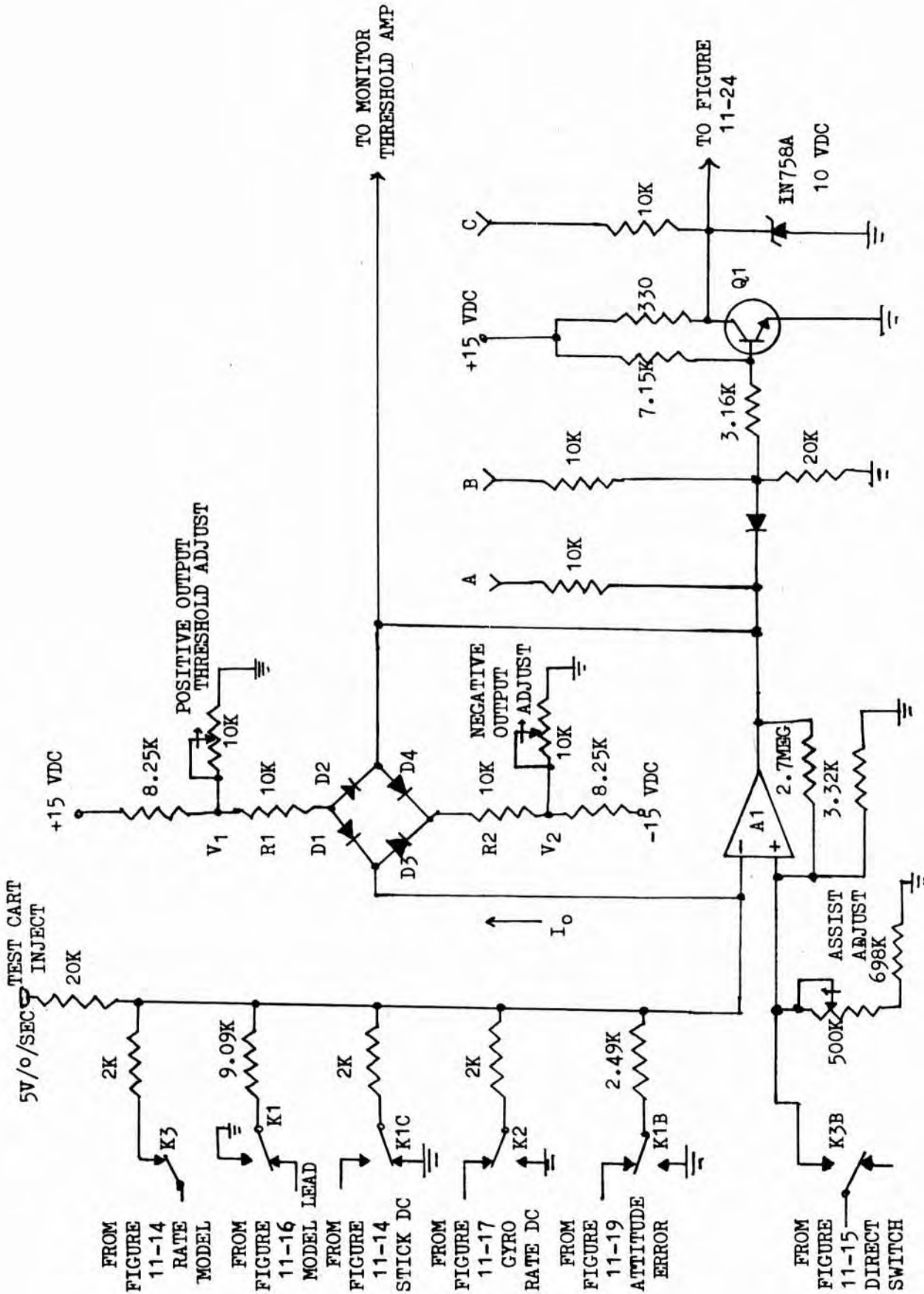


Figure 11-23. Threshold Amplifier and Inverter Circuit, Schematic Diagram

resistor R2 and diode D4 will become cutoff, since its current will be zero. Now, any more current, I_o will cause the amplifier summing junction to change voltage in a positive direction and drive the output negative. At this time, the anode of diode D2 will be approximately -10 vdc and hence diode D1 will be back biased and cutoff. The switching action is regenerative, since when the diodes begin to cutoff the feedback impedance increases, creating a higher gain and larger output which cuts the diodes off harder and again creates more feedback impedance. The switching time is limited primarily by the amplifier slew rate and a typical switching time is ten microseconds. The summing junction (negative input) is a virtual ground and provides for correct summation of the input control signals. The threshold potentiometers can be adjusted independently without any cross effect and can provide threshold currents from 50 to 500 milliamperes, corresponding to 0.2 to 2.0 degrees per second. Although the potentiometers could establish lower currents, 25 milliamperes per diode is considered a low limit for hard forward conduction. To avoid an oscillating output from ripple or random noise, a hysteresis circuit is included which feeds a portion of the output signal back to the positive base. This effectively changes the input currents and changes current I_o . The amount of current change is determined by the equivalent impedance attached to the negative base and is expressed as $\frac{12.8}{R}$ microamps. During Model mode the equivalent resistance is 500 ohms and the current becomes 25.6 microamperes, which corresponds to approximately 0.1 degree per second. When in the No-Model mode the equivalent resistance is 645 ohms, which gives a hysteresis of approximately 0.08 degrees per second.

11-101. To ensure that both the primary and monitor threshold amplifiers switch together an assist circuit is included which feeds a signal from the primary threshold amplifier's output to the positive input of the monitor channel threshold amplifier. The amount of assist can be varied

by setting a 500-kilohm assist adjustment potentiometer. During Model modes, the amount of assist can be adjusted from 0.21 to 0.36 degree per second and during No-Model model from 0.16 to 0.28 degree per second. At the minimum specified rate threshold setting of 0.5 degree per second and maximum assist, an offset margin of 0.14 degrees per second is allowed before a hardover primary threshold amplifier turns on the Monitor Channel Threshold amplifier and does not trigger the Monitor Comparator circuit. The threshold amplifier output is in trinary-single line form (-10, 0, +10 volts DC) and the jet-logic requires a binary-two line form; therefore, an inverter amplifier is included to change the threshold amplifier's negative output to a positive ten-volt output on a separate line.

11-102. The inverting amplifier is controlled by transistor Q1 and the clamping zener diode. With a non-negative output from the threshold amplifier, A1, transistor Q1 is turned ON and the inverter output, TP-C is kept near zero volts. With a negative ten-volt output from amplifier, A1, transistor Q1 is cutoff and the output, TP-C is clamped at the zener diode voltage, nominally +10 volts DC. The outputs of the pitch and roll threshold amplifier and inverter circuit are applied to pitch and roll opposing rocket inhibit logic circuits for these two channels. The yaw primary and monitor channels do not require this stage.

11-103. ROCKET INHIBIT LOGIC CIRCUIT - The rocket inhibit logic circuit (figure 11-24) routes the inputs to the correct jet rocket power amplifier inputs. Diode-Transistor Logic (DTL) is used to implement the jet logic of the circuit. For an operational analysis, assume a signal axis Pitch Up command, θ up, is given. TP-A goes to ten volts and diode D1 is back biased while diode D5 forward conducts and couples the voltage at TP-A to transistor Q2. Transistor Q2 is an emitter follower and provides approximately + 9.3 volts DC rocket firing command (TP-C) to the $A_T C_S$ rocket power amplifier. Since there are no Pitch Down or Roll Left

commands, the voltage at TP-B is approximately -0.7 volts DC which allows diode D2 to conduct and TP-E is near zero volts. This keeps Inhibit transistor Q1 off and TP-F at + 15 volts DC. Therefore, diode D3 is cut-off and allows the command signal to pass through emitter follower, Q2 as described above. Now, assume while the Pitch Up command is present, a Roll Left command is given. This will drive the voltage at TP-B to approximately +10 volts DC and back bias diode D2. With both diodes D1 and D2 cutoff, Inhibit Transistor Q1 turns ON, which turns ON, diodes D3 and D4 keeping transistor Q2 and Q3 emitters clamped at approximately - 0.6 volts DC and preventing any A or C rocket from turning ON. From figure 11-24 it can be seen that rocket cluster B_S D_T will be commanded ON instead, therefore providing one rocket per set to fire. The outputs are also routed to the monitor comparator stage.

11-104. ROCKET AMPLIFIERS CIRCUIT - There are 16 rocket solenoid driving amplifiers, (figure 11-25) one for each rocket solenoid, and each consists of a preamplifier and power amplifier section. The two sections are connected as a Darlington amplifier and drive the 15 ohm rocket solenoid coil. The required current gain of 720 is easily met by the two transistors with minimum gains of 25 for the 2N2015 and 40 for the 2N2297 throughout the operating temperature range of 0° to 140°F. A two kilohm dummy load resistor replaces the rocket solenoid coil during ground testing or whenever that particular rocket set has not been selected. Relay K2 is used for selecting the Primary or Backup Rocket Amplifiers to drive the rocket solenoids, and is controlled by the Emergency Relay Logic.

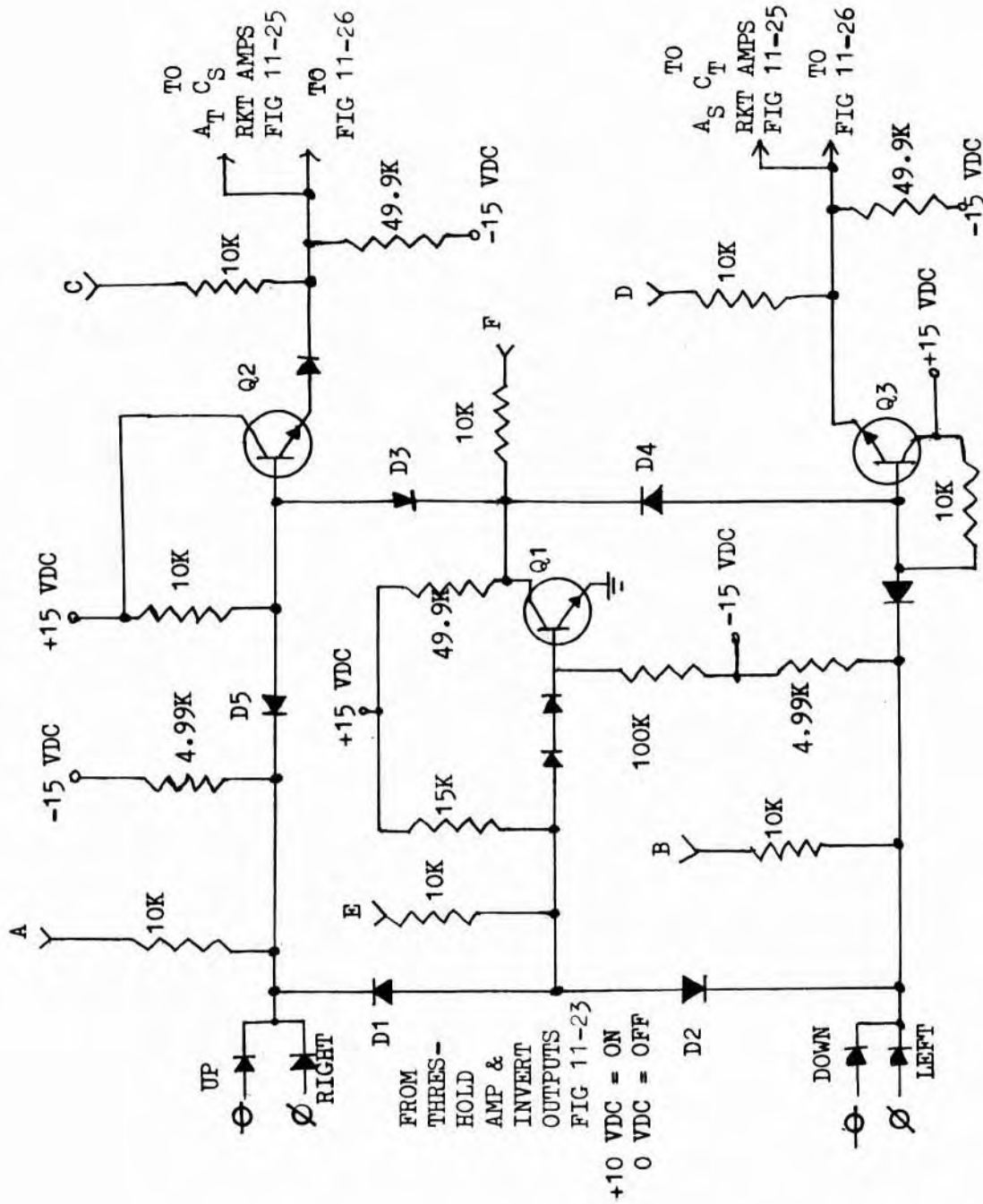


Figure 11-24. Rocket Inhibit Logic Circuit, Schematic Diagram

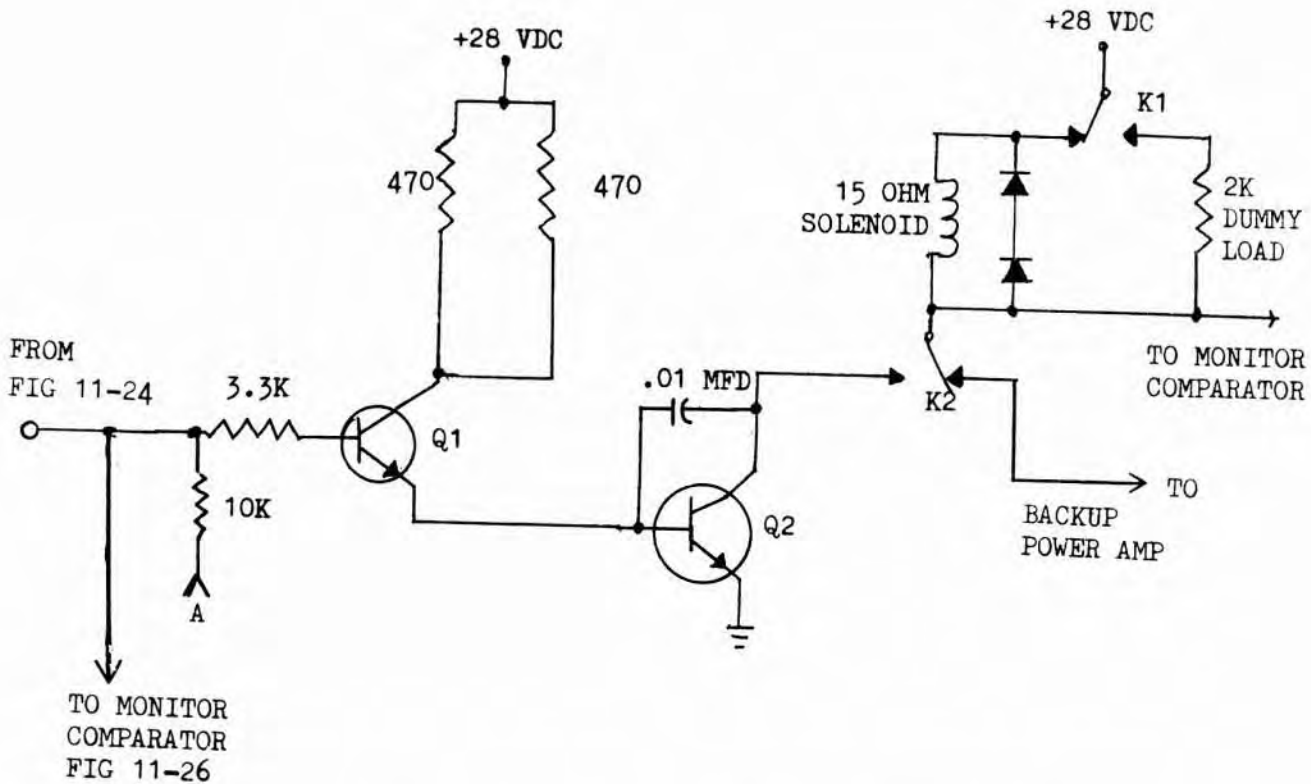


Figure 11-25. Rocket Amplifier Circuit, Schematic Diagram

11-105. MONITORING, DETECTION AND SWITCHING CIRCUITS

11-106. Circuit analysis is provided for the monitor comparator, attitude synchronizer rate switch, excess rate detector, hand controller malfunction detector, stuck valve detector, 2-jet/4-jet switching, and H_2O_2 fuel level detector.

11-107. MONITOR COMPARATOR - All input signals to the monitor comparator (figure 11-26) are binary, but the two rocket solenoid signals are at different levels than the two jet command signals. The rocket solenoid signals are approximately positive 28 volts DC with a 15-ohm or 2-kilohm source impedance when OFF and approximately a positive

0.1 volt DC with 0.5-ohm source impedance when ON. The jet command signals are positive 10 volts DC when ON and approximately zero volts DC when OFF.

11-108. Operational analysis is made with an assumption that there are no command signals from either the Primary or Monitor channels, P and M, and both sets of rockets are OFF. Transistor gate Q1 will be OFF, gate Q2 will be ON, the 330 ufd capacitor will be charged to positive 28 volts DC, and the relay coil voltage will be zero. Now assume the primary channel power amplifier output transistor shorts collector to emitter and turns ON the A_T rocket continuously. This will turn gate Q1 ON and provide a discharge path for the charged capacitor. The capacitor will discharge towards approximately positive 16 volts DC, creating an increasing voltage drop across relay K1's coil. Relay K1 will pull-in after approximately 360 milliseconds and its contact will cause the relay logic to switch to Rate Backup. Transistors Q3 and Q4 invert the monitor channel jet logic and rocket solenoid signals respectively, and transistors Q1 and Q2 function as the gating transistors which provide a ground path to discharge the 330 ufd capacitor.

11-109. ATTITUDE SYNCHRONIZER RATE SWITCH - The 400-hertz, AC rate gyro signal is amplified and then rectified by rectifier diode CR1 and filtered by capacitor C1, (figure 11-27). When the signal voltage exceeds the bias on transistor Q1, relay driver transistor Q2 conducts and relay K1 and K2 are energized. The bias on Q1 is fixed by zener diode at 7.5 volts DC. The input signal level is proportional to the rate of attitude changes. The trigger adjustment controls the gain of the input amplifier and is adjustable between 1 to 3 degrees per second. As the relay is energized, the attitude synchronizer circuits updates its attitude reference.

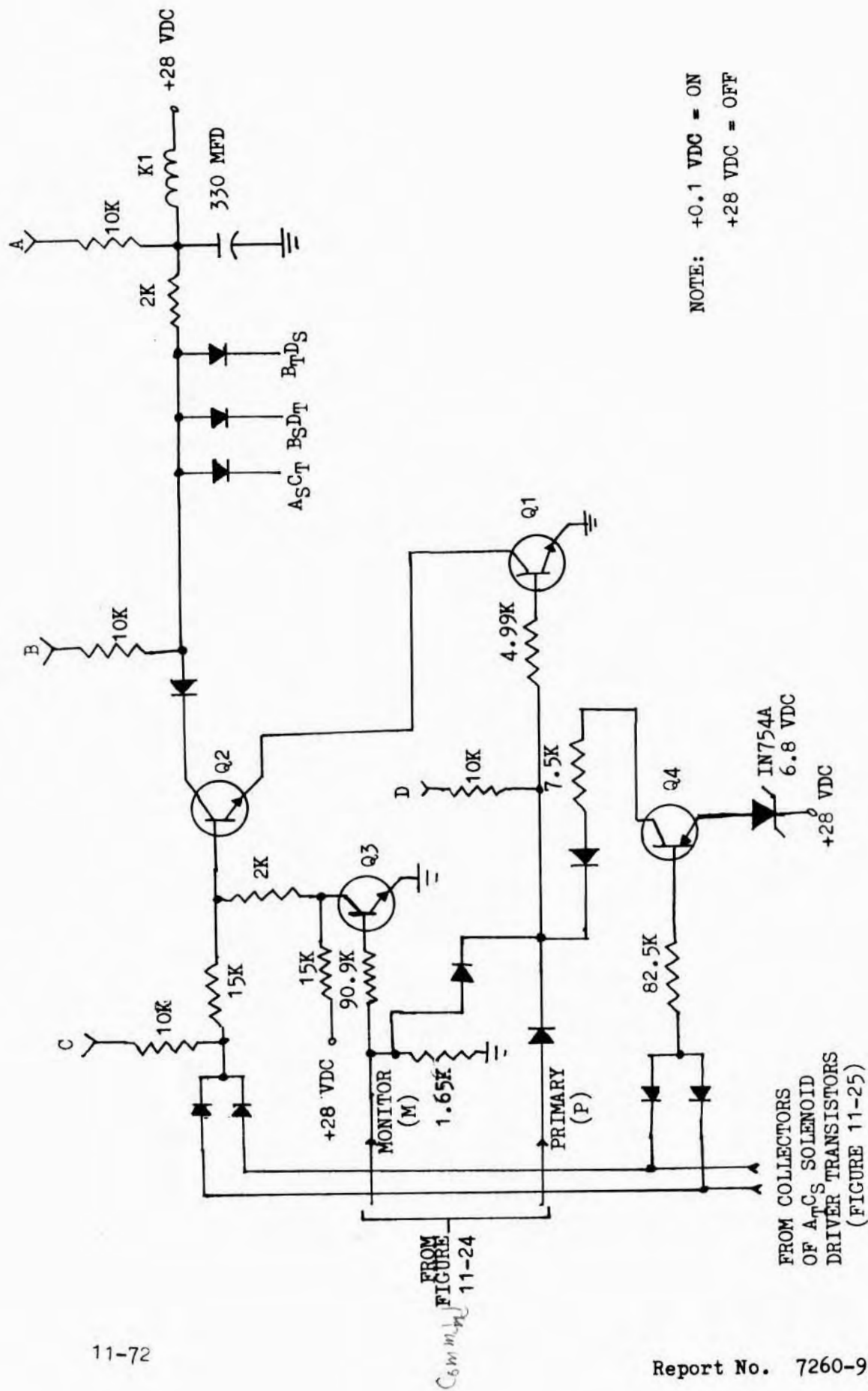


Figure 11-26. Monitor Comparator Circuit, Schematic Diagram

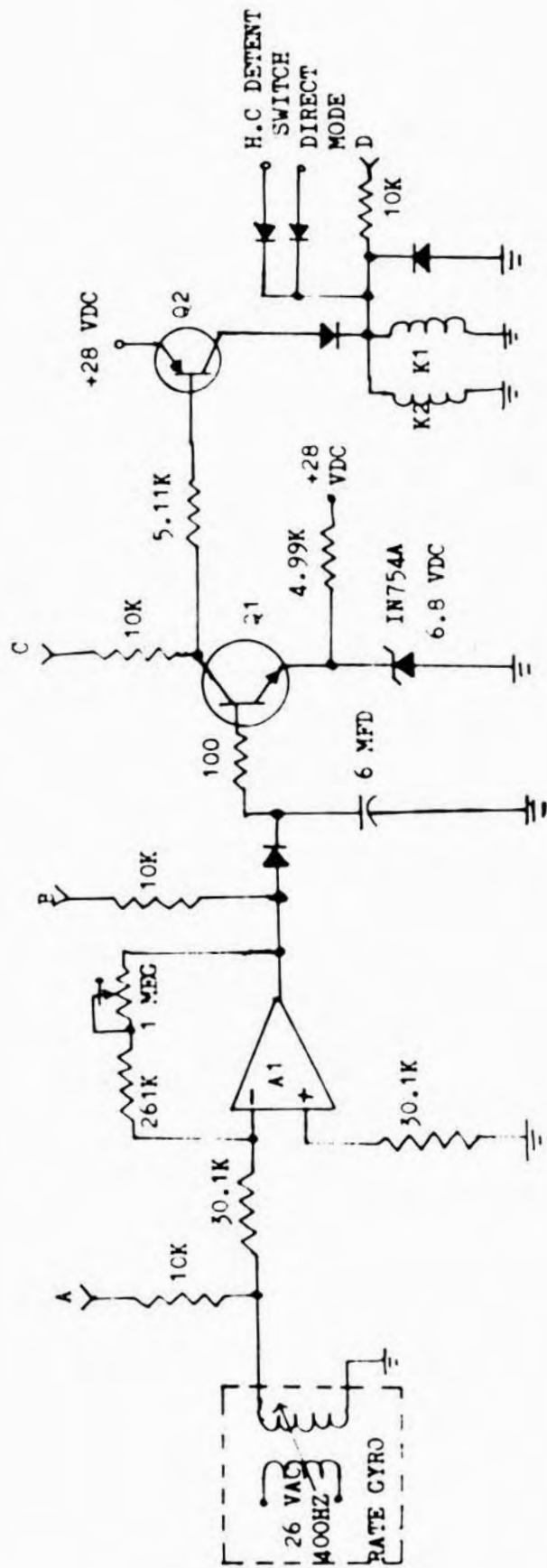


Figure 11-27. Attitude Synchronizer Rate Switch Circuit, Schematic Diagram.

11-110. EXCESS RATE DETECTOR - The excess rate detector (figure 11-28) monitors the output of the rate gyro and energizes the emergency backup relay whenever the rate exceeds a preset quantity nominally 25 ± 1 deg per second. The circuit operates by half-wave rectifying the incoming 400-hertz rate gyro signal. This gives a DC output signal from amplifier, A1 whose gain is adjustable by using the 22-turn trigger adjustment potentiometer. The output of amplifier A1 turns on the trigger circuit and DC current amplifier Q1, Q2 when it exceeds approximately positive 7.6 volts DC. The positive 28 volts DC output of transistor Q2 energizes an approximately 600-ohm relay coil, and causes the relay logic to switch to the required emergency condition. The adjustment potentiometer allows setting of trigger from 24 to 26 degrees per second.

11-111. The relationship between the excess rate circuits for the primary monitor channel and the backup channel is shown in figure 11-29. When an approximately 22 degree per second rate gyro output (roll or pitch) is detected by the monitor excess rate circuits, K17 is energized. Relay K17 C contacts serve to latch K17 and de-energize relays K1, K3 and K4 in the backup electronics package (Primary/Backup switch S7 in PRIMARY position as shown). Relay K1 contacts applies positive 28 volts DC to illuminate the AUTO PILOT BACK UP indicator. The contacts of K3 and K4 are switched from the primary rocket amplifiers to the backup rocket amplifiers. A backup gyro hardover condition, a power failure in the attitude gyro package, or any other cause of an excess rate output from the backup excess rate detector automatically places the system into the primary channel (when Primary/Backup switch is in PRIMARY position). Relay K4, located in monitor electronics is energized and contacts B applies positive 28 volts DC to the relays K1, K3, and K4, in the backup electronics package. Relay K4 A contacts applies a ground to the GYRO FAILURE indicator. If the output from the backup excess rate detector is momentary, then the system returns to the backup mode. When

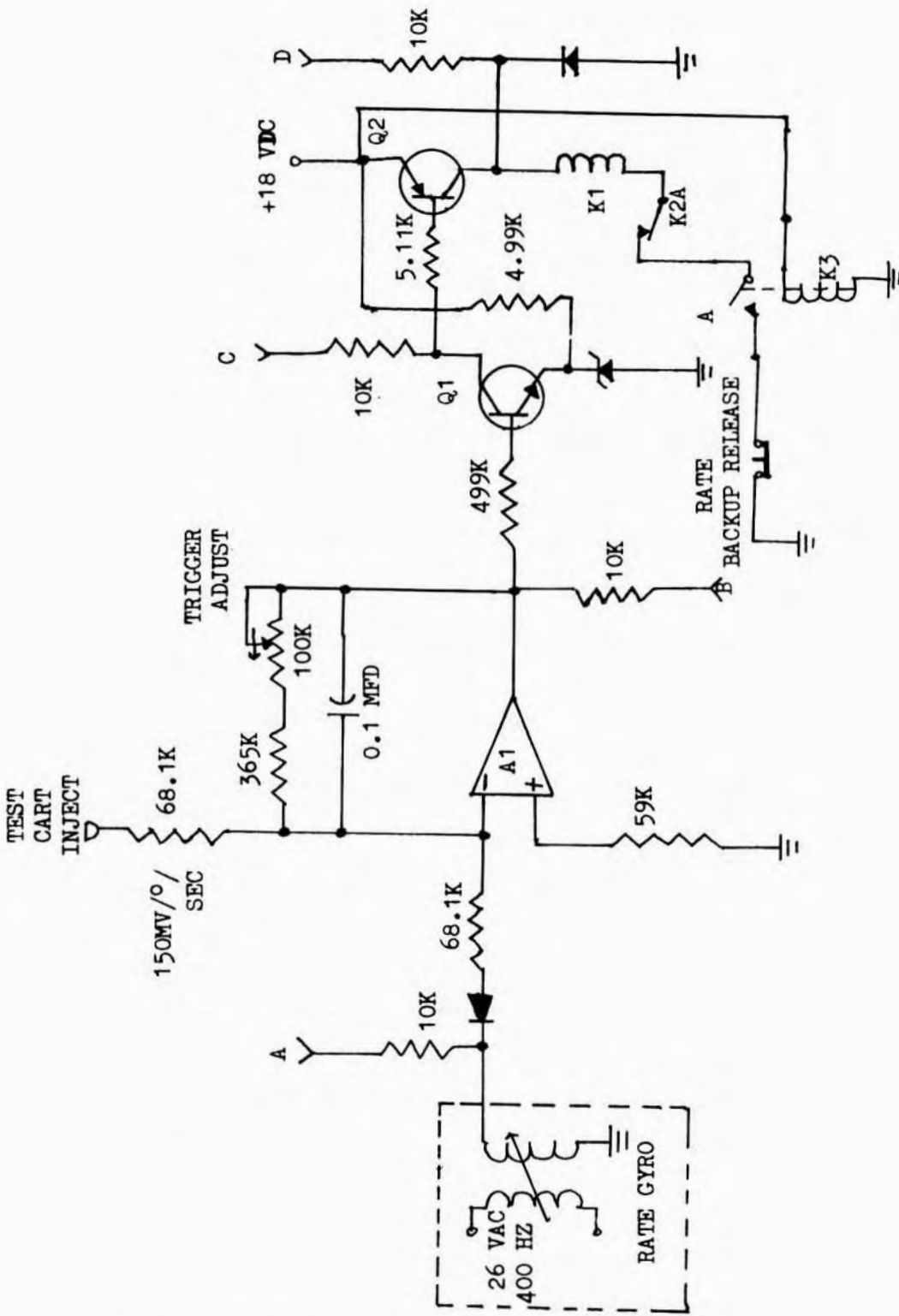


Figure 11-28. Excess Rate Circuit, Schematic Diagram

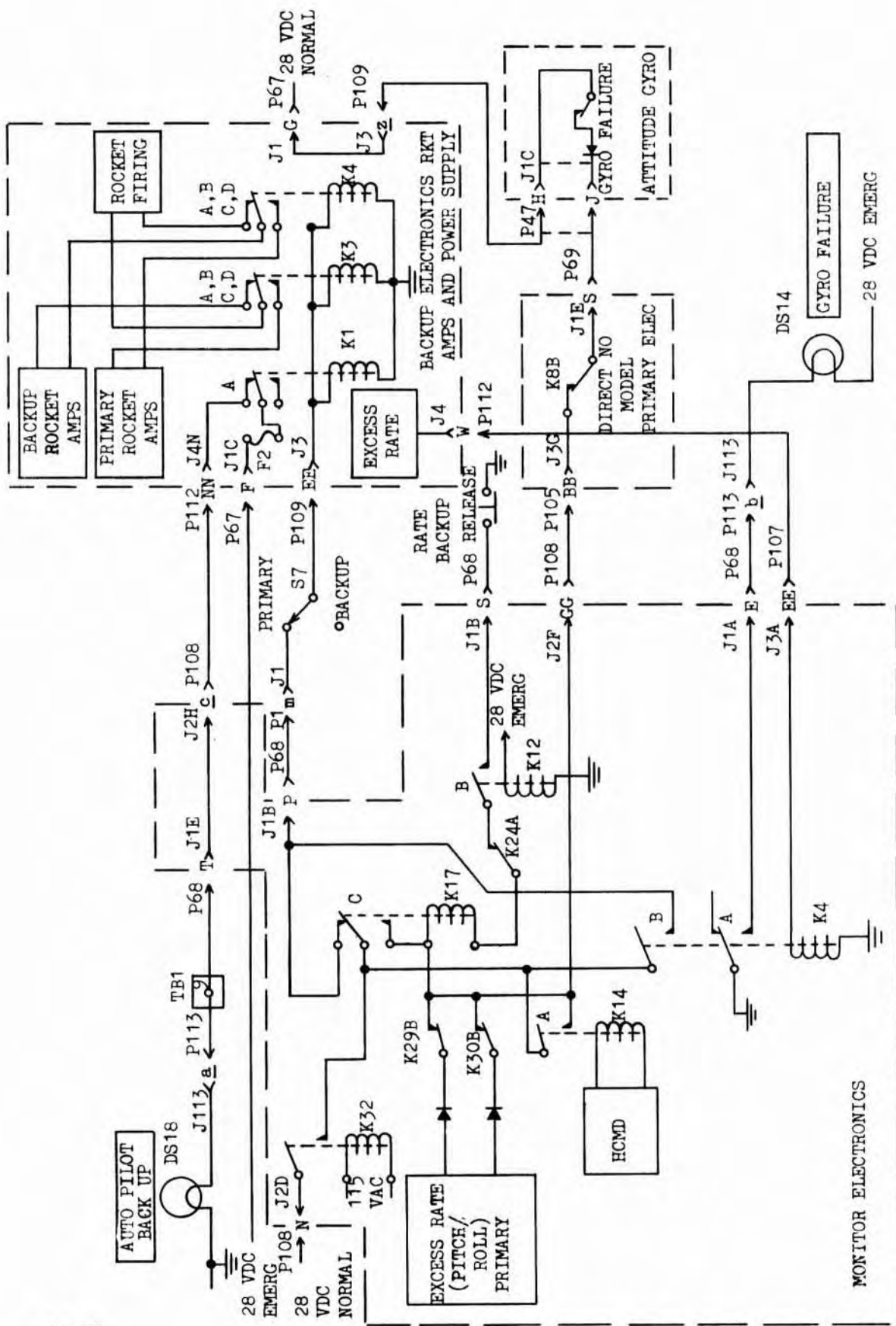


Figure 11-29. Typical Excess Rate Detector Relay Switching Control, Schematic Diagram

the GYRO FAILURE indicator remains illuminated, indicating a continuing backup excess rate detector output, the system remains in primary. The appropriate Attitude Control Mode switch shall be placed in the DIRECT position by the pilot. Control of relay K17 (figure 11-29) is also accomplished through operation of the hand controller malfunction detector circuit.

11-112. HAND CONTROLLER MALFUNCTION DETECTOR CIRCUIT - The hand controller malfunction detector (HCMD) (figure 11-30) is designed to detect hardover or open conditions in either the hand controller's linear transformer (synchro) or functional direct switch (FDS) and switch the ACS system (single axis) to a safe backup mode. This is accomplished by comparing three pieces of information (signals) from the hand controller in two separate detection circuits. One circuit compares the synchro signal with a logic direct switch (LDS) signal and is the synchro/direct switch comparator. The LDS is the same type switch as the FDS, except it is not used for firing rockets or controlling the vehicle; it is only used in the HCMD logic circuits. The other circuit compares the two direct switch signals, LDS and FDS, and is the direct switch comparator. Each comparator circuit will be considered separately.

11-113. The direct switch comparator operates by adding the voltages from the LDS and FDS switches, and applying the resultant voltage to a fixed threshold trigger circuit. Since the LDS and FDS switches are excited with equal but opposite polarity voltages the sum at TP-K will always be approximately zero. However, if either switch sticks open (0 volts DC) or hardover (15 volts DC) the other still continues to operate and the voltage at TP-K will increase. The trigger voltage, approximately 3.3 volts DC at TP-K, is set low enough so that the 7.5 volts DC resulting from a switch malfunction can overcome it, yet power supply and circuit offsets or noise during normal operation will not trigger it. The trigger circuit amplifier output, TP-M is applied to relay K1 contact which allows

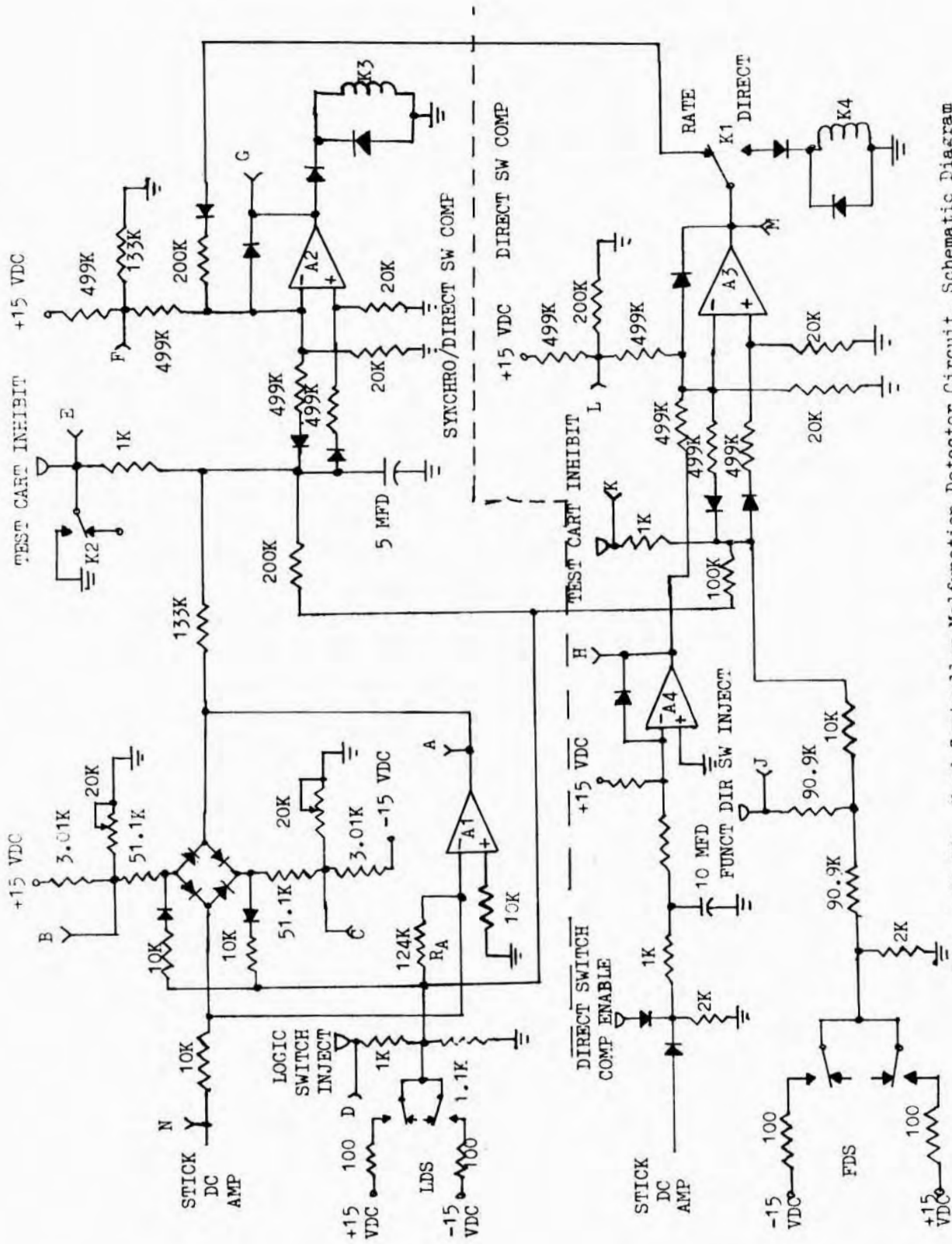


Figure 11-30. Hand Controller Malfunction Detector Circuit, Schematic Diagram

the signal to energize relay K4 and switch the ACS to Rate Backup mode if operating in Direct mode; or if operating in Rate mode an inhibit signal is sent to the synchro/direct switch comparator circuit. This inhibit signal is necessary in the case where the LDS malfunctions. Since it is used in common with both comparators, each would attempt to switch the ACS system. However, there is no need to switch while operating in Rate mode since the synchro is still functional. Another need for the inhibit arises if a FDS malfunctions while operating in Rate mode. In this case it is mandatory that relay K3 not be energized, since it will latch the system into the Direct mode which already has a bad FDS. Since the LDS and FDS are not exactly matched and therefore break and make at slightly different amounts of hand controller motion, an enable circuit amplifier A4, is included which keeps amplifier A3 from switching for hand controller deflections less than approximately 4.5 degrees. An enable input and direct switch inputs are included for testing of the direct switch comparator from the test cart.

11-114. The synchro/direct switch comparator operates by changing the linear DC stick voltage into trinary, digital form, adding the LDS switch voltage to it, and applying the resultant voltage to a fixed threshold trigger circuit. The trinary, digital signal is obtained from amplifier, A1 by using a threshold or deadzone amplifier adjusted to switch at about the same time as the LDS switch. Since the amplifier output, TP-A is at positive 10, 0 or negative 10 volts DC level, and the LDS switch is at a positive 15, 0, or negative 15 volts DC level, scaling resistors are used to create a zero sum for normal hand controller operation. A five microfarad capacitor is used to create a delay before triggering amplifier A2. The trigger voltage, approximately 3.1 volts DC at TP-E, in conjunction with the R-C time constant determines the time delay which is typically 360 milliseconds for a hardover LDS switch and 300 milliseconds for a hardover synchro signal. When amplifier A2 is triggered it drives relay K3 which latches the malfunctioning axis into the Direct-No

Model mode. This mode can only be reset by turning off power or energizing a release relay from the Avionic test cart. Since the LDS switch possesses hysteresis (approximately 0.3 deg) an assist path is added from the switch to the synchro threshold amplifier input through assist resistor, R_A . This allows the LDS switch and threshold amplifier to switch together and avoid creating a pseudo backup within the regions of the hand controller where switch hysteresis is effective. The assist resistor is scaled such that it cannot overcome the threshold by itself, but will add enough signal to the synchro input signal to allow simultaneous switching of amplifier A1 and the LDS. Diodes D1 and D2 are included in order to maintain a nearly equal time delay for all Synchro or LDS type failure conditions. This is done by keeping amplifier A1 from generating an output of the same polarity as the LDS, and prevents charging the 5 microfarad capacitor faster than the single hardover signal case. Amplifier A1 is kept at zero by feeding the LDS signal through diodes D1 and D2 into the threshold bridge and increasing the equivalent threshold current such that the synchro signal cannot overcome it and turn the amplifier ON. It should be noted that the synchro/direct switch comparator is always enabled, unlike the direct switch comparator which is only enabled when the hand controller is deflected beyond 4.5 degrees.

11-115. STUCK VALVE DETECTOR CIRCUIT - The stuck valve detector (figure 11-31) senses when any of eight pairs of opposing rockets are firing, and after a fixed time delay energizes the stuck valve relay. This is accomplished by monitoring each of the five kilohm attitude rocket pressure transducer potentiometers with two input diode AND circuits. The output of each AND circuit is then OR'd into the input of a trigger circuit. Consider the opposing rocket pair $A_T C_S$: when both rockets are off the voltage at the arm of each potentiometer is about negative 4.7 volts DC, allowing diodes D2 and D3 to forward conduct and put approximately negative 4.0 volts DC at TP-A. This is not enough to turn ON transistors Q1, Q2, which are referenced to negative 5.0 volts DC, and

therefore the circuit remains untriggered. If rocket A_T now fires, increasing the potentiometer voltage to say positive 1 volt DC, and rocket C_S remains off at negative 4.7 volts DC, on the potentiometer arm, TP-A is still held at negative 4.0 volts DC by diode D3 and diode D2 will cutoff. Since TP-A voltage is unchanged, the circuit will again not be triggered. However, if both rockets turn ON such that the voltage at TP-A increases to negative 2.9 volts DC at the potentiometer arm and is equivalent to ten pounds of rocket thrust. The time-delay operates as follows: initially the 36 microfarad timing capacitor is uncharged, all transistors are off and TP-B and TP-C are at positive 22.5 volts DC. When transistor Q2 is turned ON, the voltage at TP-B becomes negative 4.7 volts DC, and the capacitor begins to charge towards this voltage with approximately a 580 millisecond time constant. When the capacitor charges to about positive 8.2 volts DC, transistor Q3 conducts and latches the circuit ON by feeding a regenerative current through the 1N4104 zener diode back to Q1 base. The time-delay required to turn ON transistor Q3 is nominally 208 milliseconds. When relay K1 is energized it illuminates the VALVE STUCK indicator and switches the system to both sets of rockets. Diode D1 provides a quick discharge path (72 millisecond time constant) for the delay capacitor. This helps to prevent overlapping pressure decay pulses from falsely triggering transistor Q3.

11-116. 2-JET/4-JET SWITCHING CIRCUIT - The 2-jet/4-jet switching circuit (figure 11-32) is designed to energize relay K1 whenever the absolute value of the difference between the synchro (stick) command and the model output is greater than approximately one degree per second. This is accomplished by applying the DC stick and model signals to difference amplifier A1 with a gain of 3.65. The output of amplifier A1 goes to trigger amplifier, A2 whose output then drives current amplifier Q1, Q2. The trigger amplifier's output switches from negative 0.5 volts DC to positive 10.5 volts DC, when the voltage at TP-A exceeds positive 1.83 volts DC. The circuit's output transistor drives relay K1 which switches

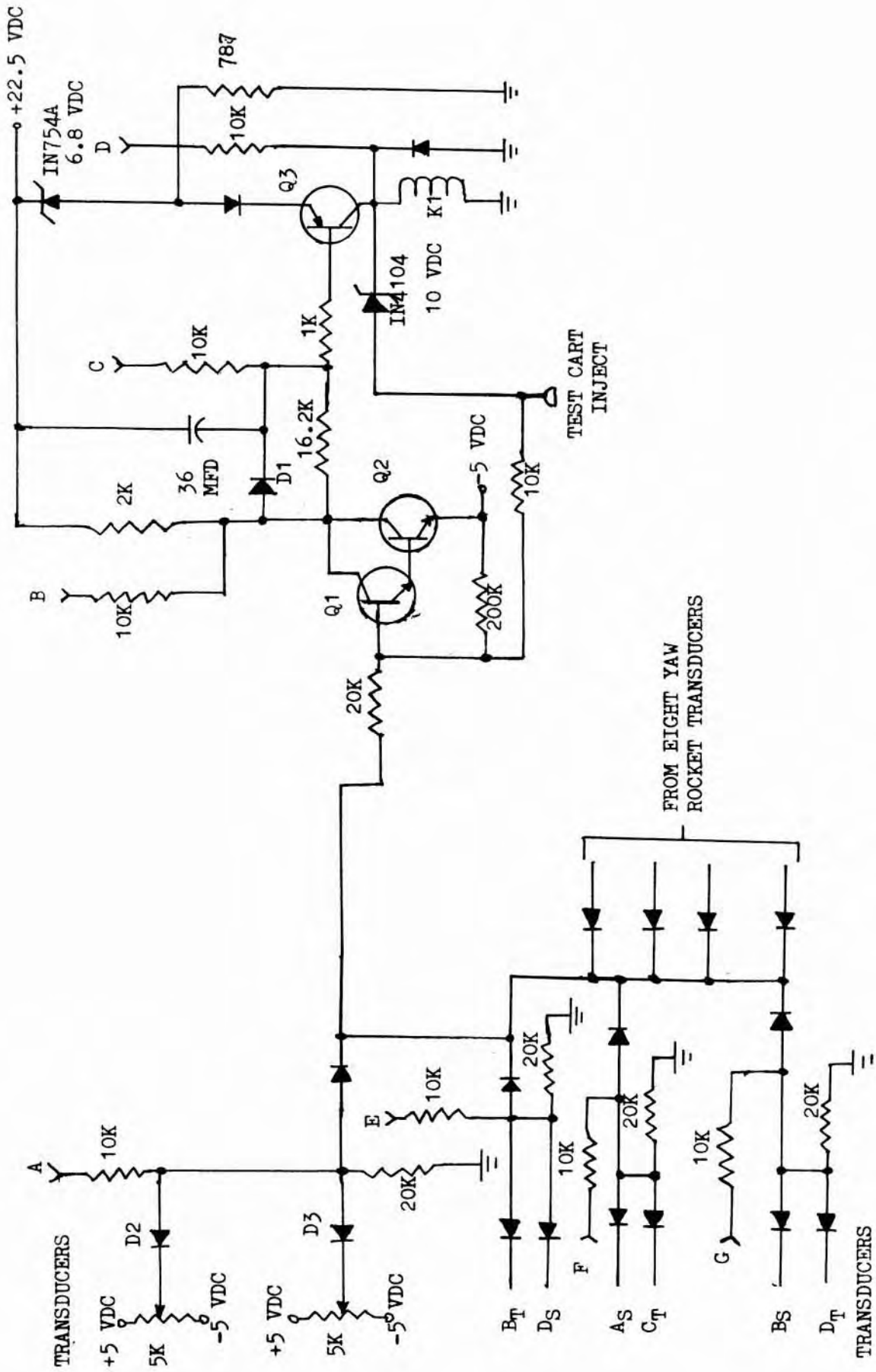


Figure 11-31. Stuck Valve Detector Circuit, Schematic Diagram

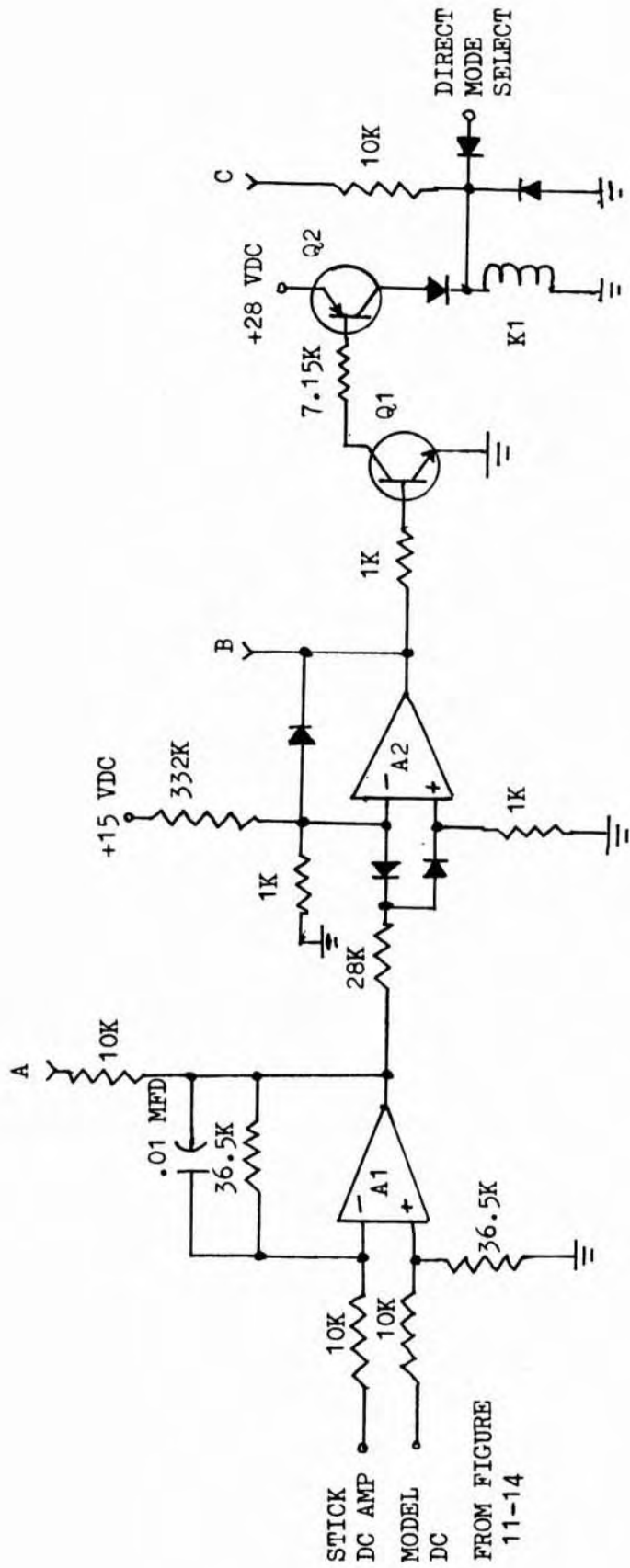


Figure 11-32. 2-Jet/4-Jet Switching Circuit, Schematic Diagram

the model integrator's input resistor and doubles the model slope to simulate 4-jet operation.

11-117. H₂O₂ FUEL LEVEL DETECTOR CIRCUIT - The hydrogen peroxide fuel level detector circuit (figure 11-33) computes the fuel consumed by the sixteen attitude rockets and the two lift rockets. This is accomplished by monitoring the output transistor of each rocket power amplifier and a lift rocket chamber pressure transducer, converting the ON signals to currents representing the burnoff rates and summing these currents in a chopper stabilized integrator amplifier. A T-resistor network is used to bias any OFF or quiescent drifts, and a slew switch is used for adjustment of the integrator output and hence the indicator reading. The output is applied to a bias and scale factor network to make it compatible with the cockpit fuel remaining indicator.

11-118. For circuit analysis, assume all rockets are OFF except A_T. With A_T ON the inverter transistor Q1 is turned OFF and the voltage at TP-A is clamped at ten volts by the 1/4 M10Z1 zener diode. TP-B will increase by 100 millivolts and will be the input signal to the integrator input network. Relay K1 is energized if the test rockets are selected, relay K2 if standard rockets are selected, both relays if the ACS Safe switch is in SAFE position, and neither relay is energized if both sets are selected. Assume test rockets are selected, thus the input path is through relay K2A contact and a 22-turn, 500-kilohm trim potentiometer is used for adjusting the burnoff rate from 0.57 to 0.82 lb/sec. Similarly, for a given lift rocket thrust, the 22-turn, 10-kilohm adjustment potentiometer can be set using a scale factor of 57 MV/LB/SEC at TP-E. The integrator output is scaled for zero volts DC to be equivalent to 700 pounds and negative 10 volts DC to be equivalent to zero pounds.

11-119. JET ENGINE ATTITUDE CONTROL CIRCUITS

11-120. Circuit analysis is provided for these circuits partly in the same order as the block diagram analysis, however, as a typical circuit is usually discussed, a continuous, operational sequence is not necessarily followed in the discussion.

11-121. EXCESS ANGLE WITH RESPECT TO VERTICAL - The excess angle circuit (figure 11-34) computes the pitch and roll jet engine angle with respect to a local vertical reference (defined by the vertical gyro) and energizes emergency relay K1 (K10 in figure 11-35) whenever either the pitch or roll angle exceeds 15 degrees. The circuit functions by algebraically adding the gimbal potentiometer and gyro DC signals and applying the sum to a threshold bridge amplifier which is scaled (47 microamperes) to switch at 15 ± 1 degrees. If the amplifier output TP-A is positive it is applied to relay driving transistor, Q2; if the output is negative it is applied to inverting amplifier, Q1 and then passed to transistor Q2. An OR diode network is used to connect the pitch and roll excess angle amplifier outputs to the driving transistor, Q2.

11-122. The emergency relay K1 (K10 on figure 11-35) contacts applies positive 28 volts DC to the MAX ENGINE TILT indicator and relay K13 (figure 11-35). Relay K13 applies positive 28 volts DC from the Gimbal Lock switch (in OFF position) and de-energized contacts of relay K5 through diode CR17 to the emitter of transistor Q1 in the Gimbal Lock Warning Diode Box, and to the gimbal lock solenoid L1, which energizes, placing the engine in gimbal locked (engine centered) configuration. The conduction of Q1 through diode CR39 and the EMERG GIMBALS LOCKED indicator illuminates that indicator. Refer to section V for a description of the hydraulic sequence.

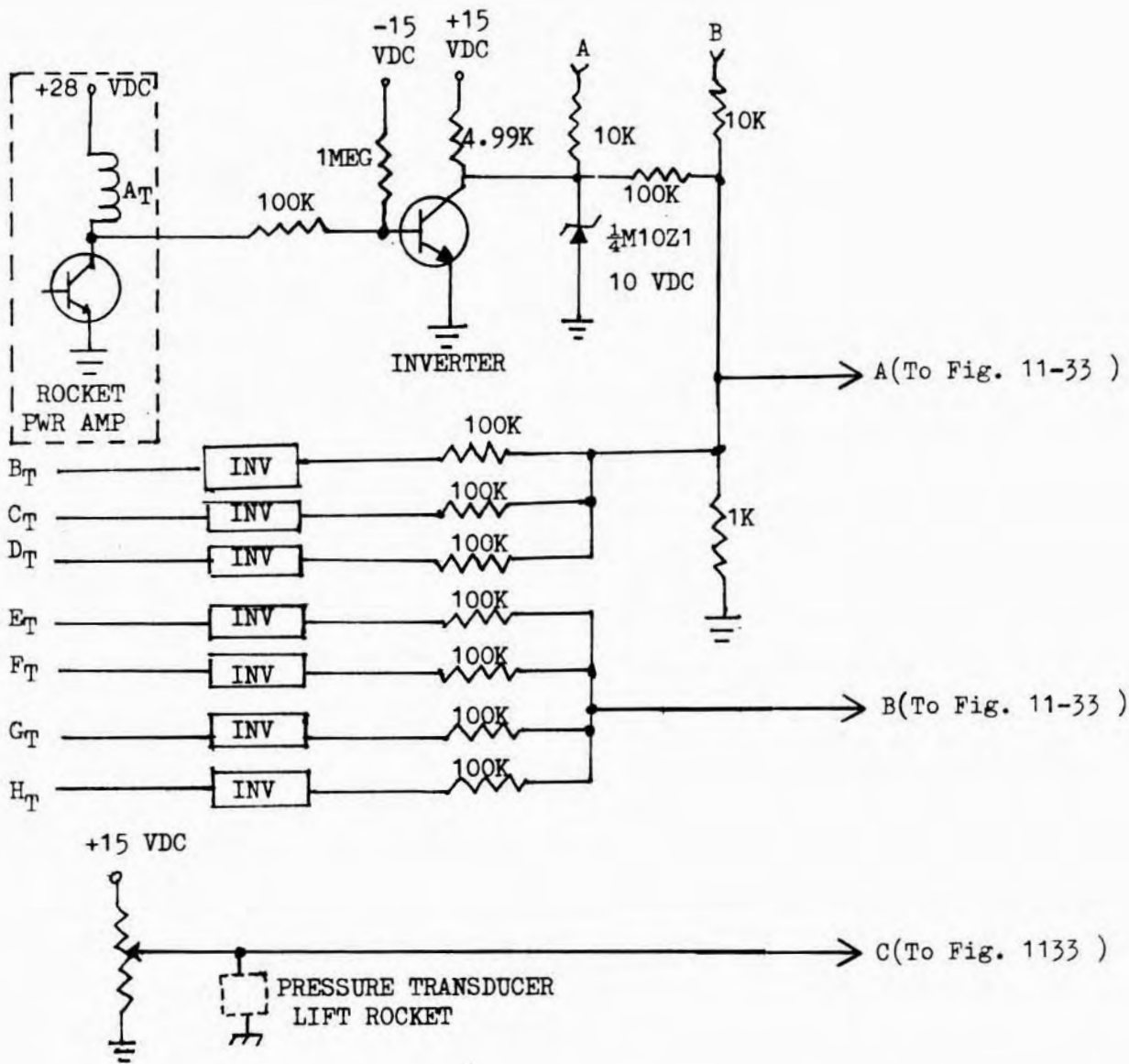


Figure 11-33. H₂O₂ Fuel Level Detector Circuit, Schematic Diagram

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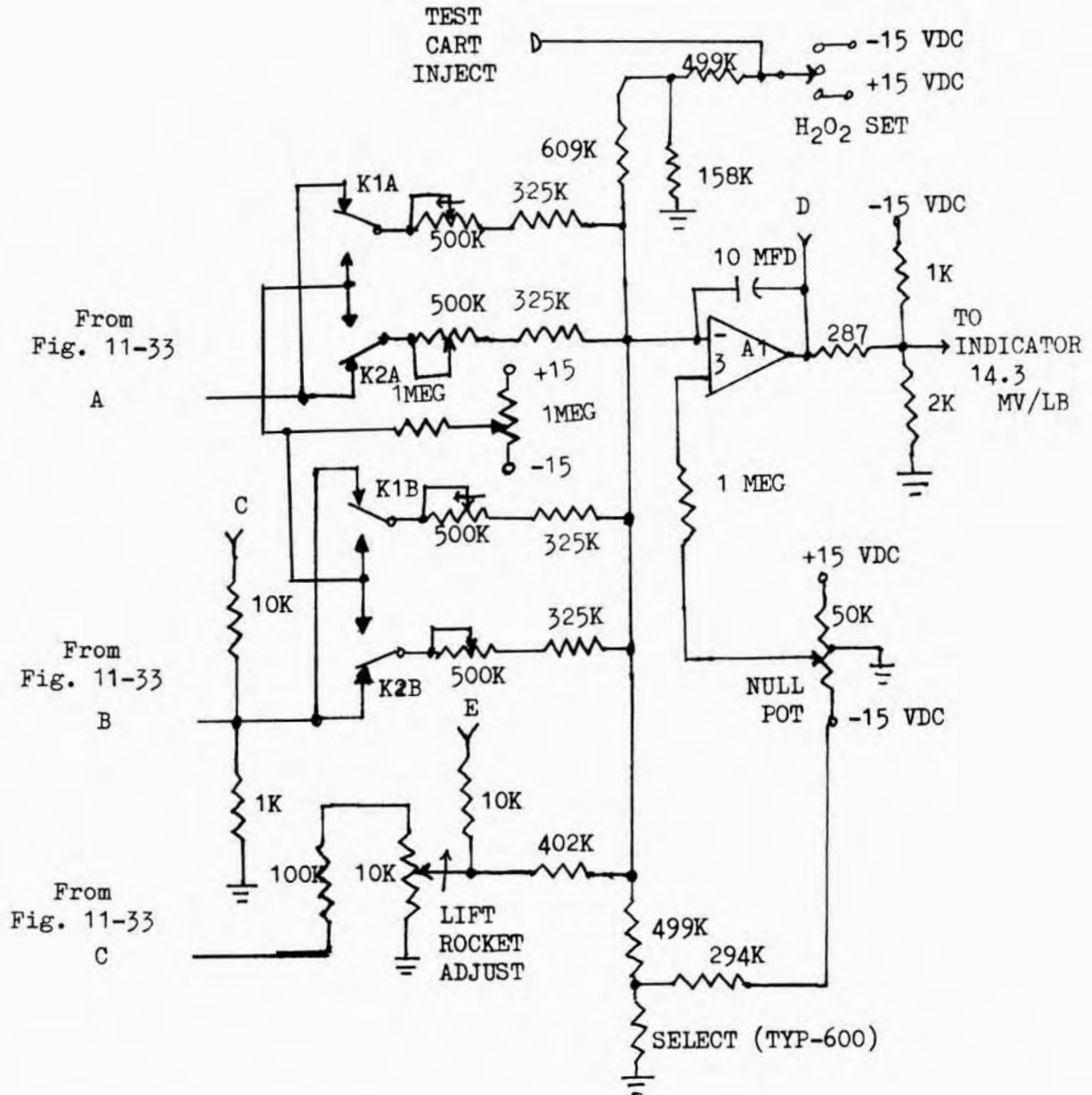


Figure 11-33. H₂O₂ Fuel Level Detector Circuit, Schematic Diagram

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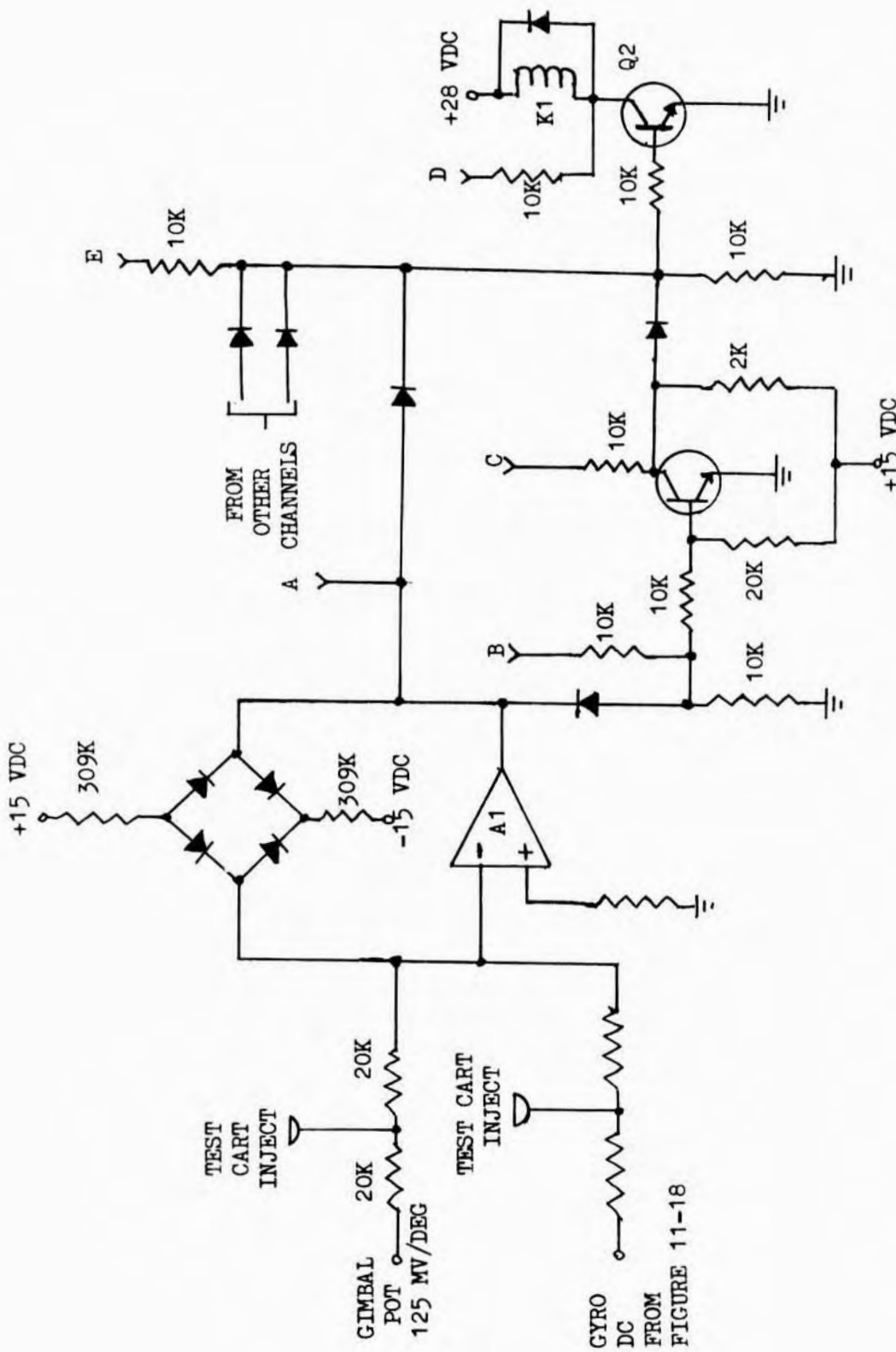


FIGURE 11-18

Figure 11-34. Excess Angle With Respect to Vertical Circuit, Schematic Diagram

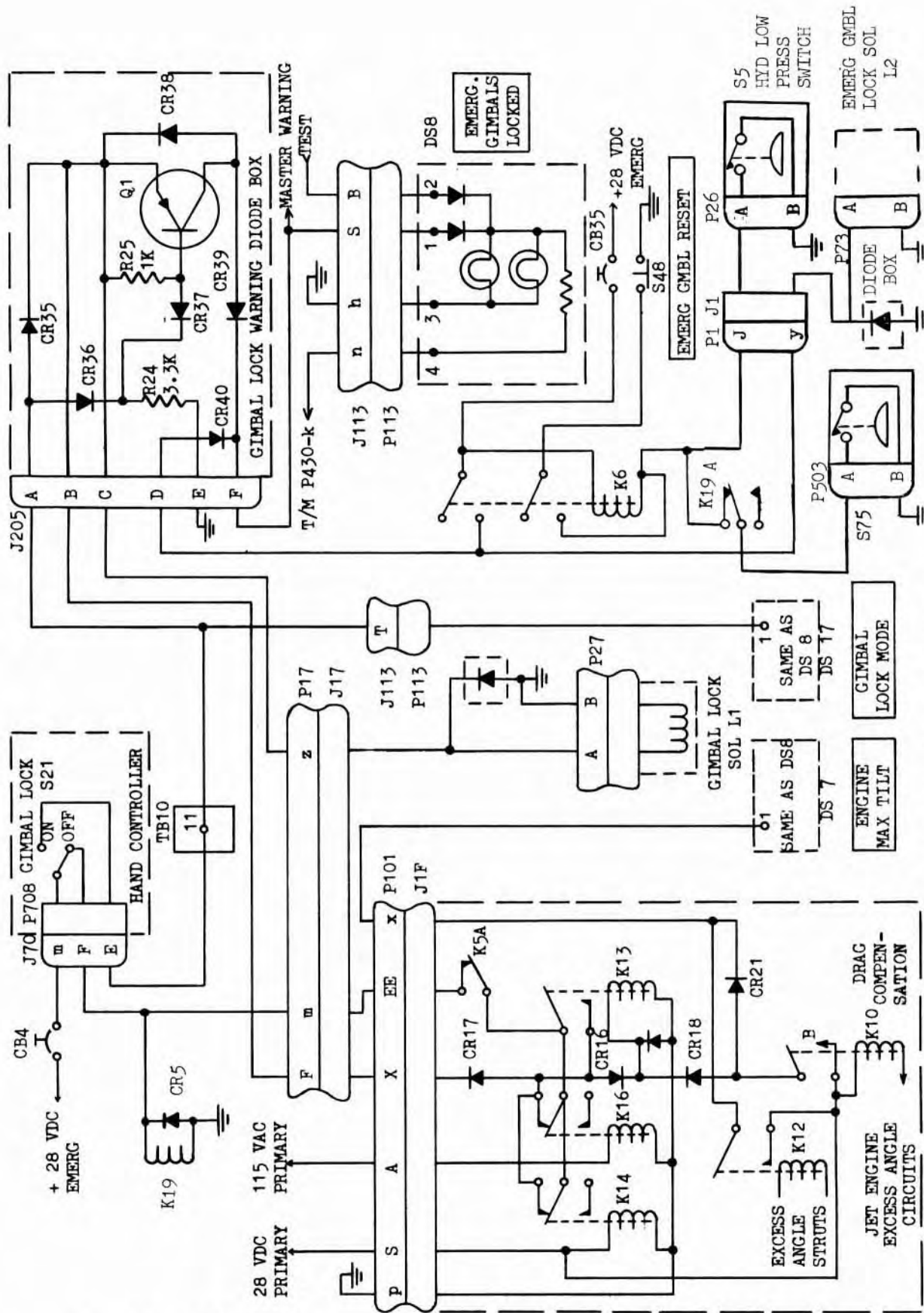


Figure 11-35. Gimbal Lock Control Circuits, Schematic Diagram

11-123. EXCESS ANGLE ALONG STRUTS CIRCUIT - The excess angle along the strut circuit (figure 11-36) computes the sum of the absolute pitch and roll gimbal angles, and energizes relay K1 whenever this sum exceeds 64 degrees. It should be noted that a linear and not vectorial sum is computed. The computer is mechanized by feeding the pitch and roll gimbal angle potentiometer signals through steering diodes to the input of amplifier, A1. These signals are then compared to a fixed trigger current and when they exceed an equivalent sum of 64 degrees the relay's transistor driver, Q1, is turned on; thus energizing relay K1. (K12 in figure 11-35) The relay contacts apply positive 28 volts DC to illuminate the MAX ENGINE TILT indicator.

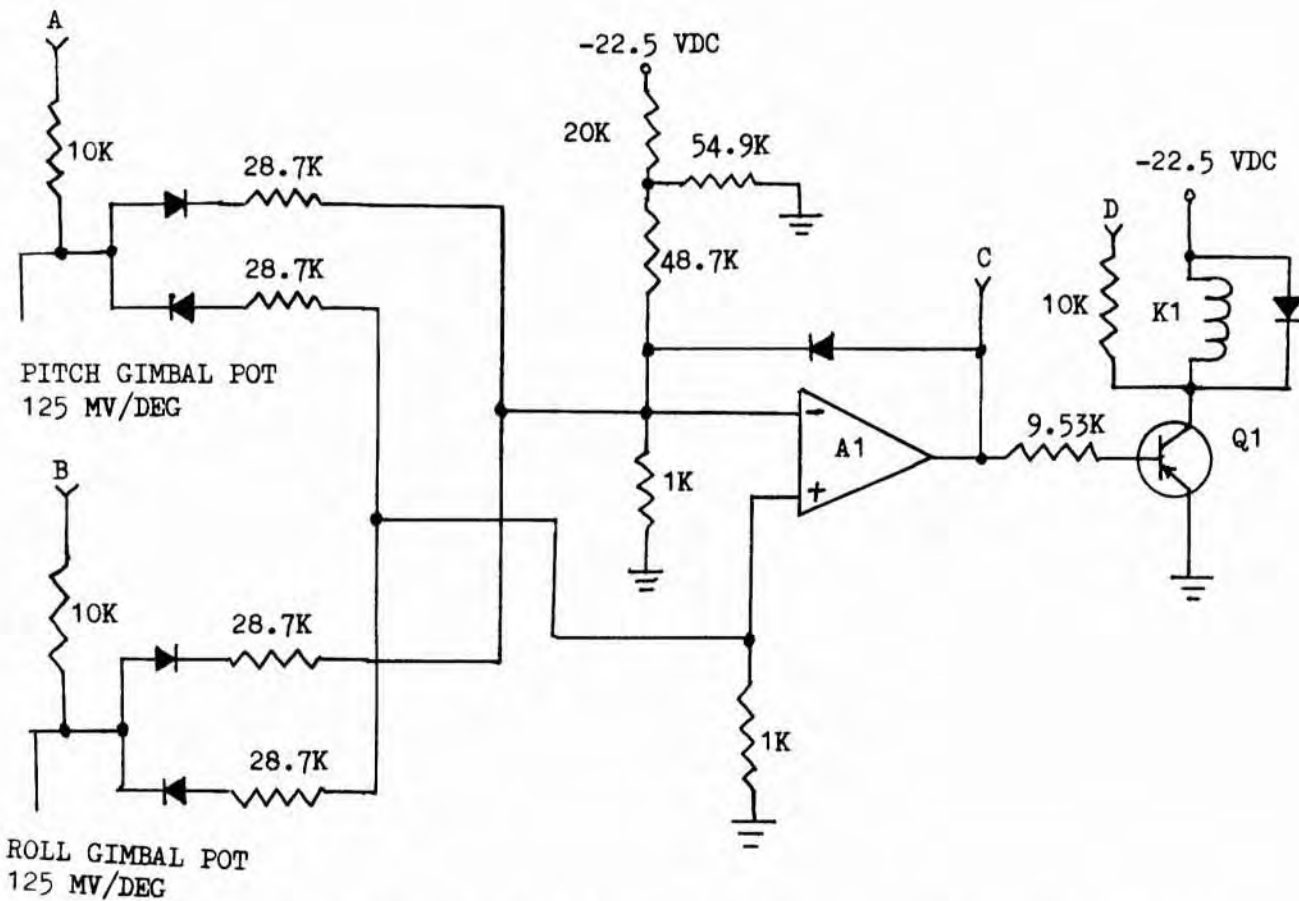


Figure 11-36. Excess Angle Along Struts Circuit, Schematic Diagram

11-124. SUMMING AMPLIFIER CIRCUIT - The summing amplifier (figure 11-37) functions as a summing amplifier only during Local Vertical mode. When relay K1A contacts close, the attitude gyro signal from the vehicle attitude control system is applied, in conjunction with an input from the gimbal potentiometer to the negative input of the summing amplifier. In the Engine Centered mode, the only input is the gimbal potentiometer signal. During Lunar Simulation mode, the summing amplifier is not used. The amplifier provides a gain of 7.88 volts DC per radian. This output is applied to the actuator drive amplifier.

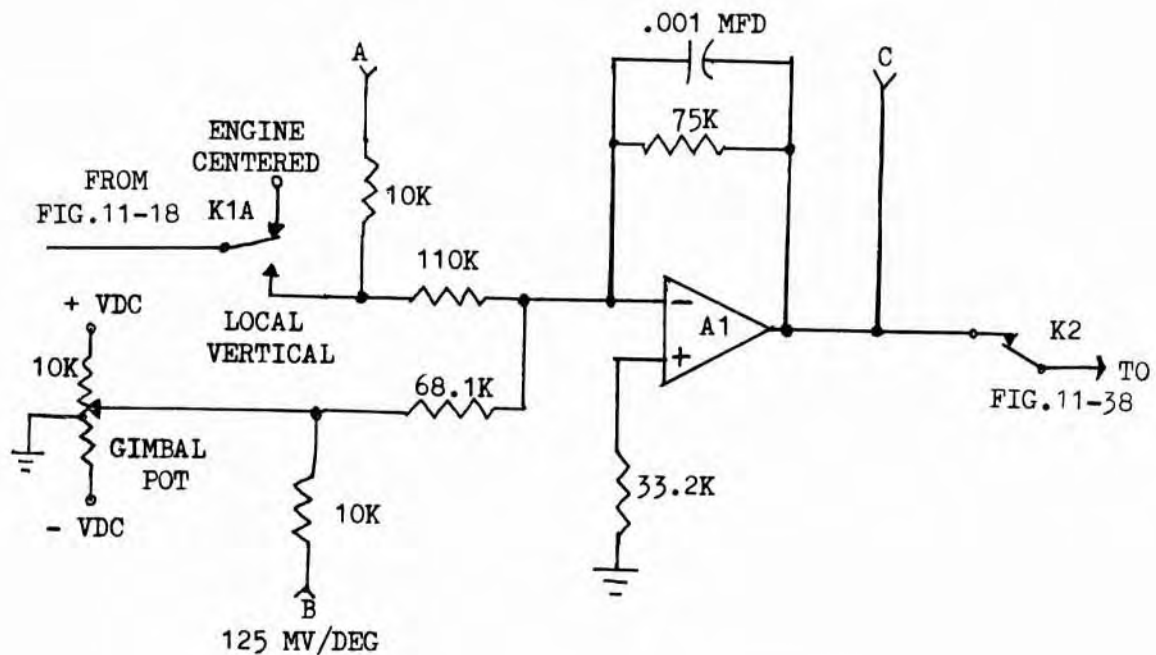


Figure 11-37. Summing Amplifier Circuit, Schematic Diagram

11-125. ACTUATOR DRIVE AMPLIFIER CIRCUITS - The actuator drive amplifier consists of a comparator network and integrator (figure 11-38) and a valve coil and lead circuit (figure 11-39) pass filter. The network serves as (1) a servo filter which maintains a low bandpass, and (2) a ripple filter for the 400-hertz half-wave demodulated signal from the gimbal resolver when operating in Lunar Simulation mode. The integrator amplifier is used to ensure a low static error since the servo flow valve has a current deadzone. In other words, without an integrator a low DC offset could exist which would not be large enough to overcome the flow valve's current threshold and therefore a steady state engine position offset error would exist. A chopper stabilized low drift amplifier is used as the integrator amplifier and ensures minimum integrating error. A null adjustment potentiometer is included to zero any integrator or circuit drift. Relay contact K1A is used for resetting or zeroing the integrator when operating in the Gimbal Locked mode, since during this time the integrator's output could become large and create a large transient engine movement when Gimbal Lock was released.

11-126. The valve coil amplifier is a current driving amplifier capable of supplying a maximum of five milliamps to the hydraulic actuator servo valve coil. The two servo valve coils are connected in series which create a maximum of ten milliamps differential current (the rated valve current). The Lead circuit is formed by a 30.1-Kilohm resistor and 0.68-microfarad capacitor parallel input path. The lead is required to compensate for other lags or delays in the jet stabilization loop. The DC gain of this amplifier circuit is 2.21 milliamperes per volt.

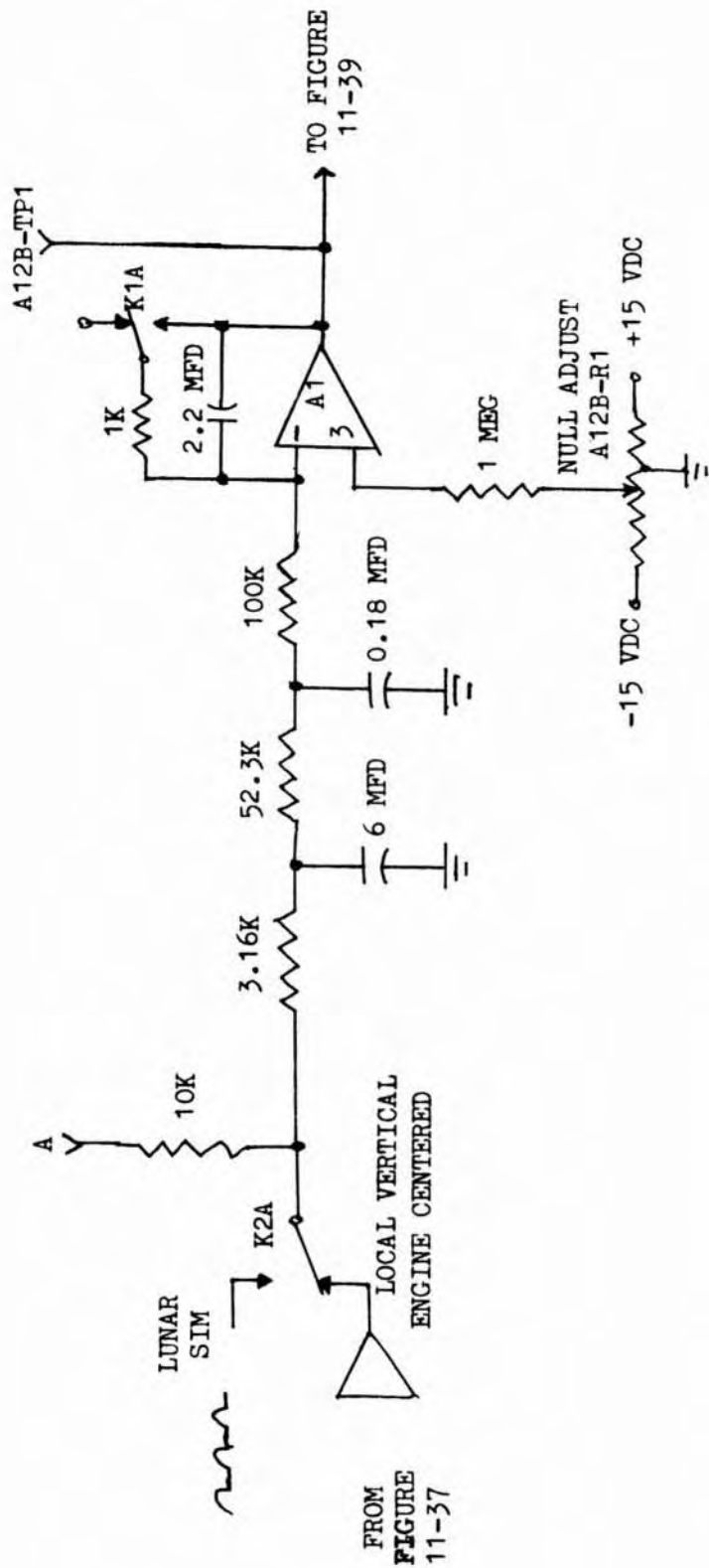


Figure 11-38. Compensation Network and Integrator Circuit, Schematic Diagram

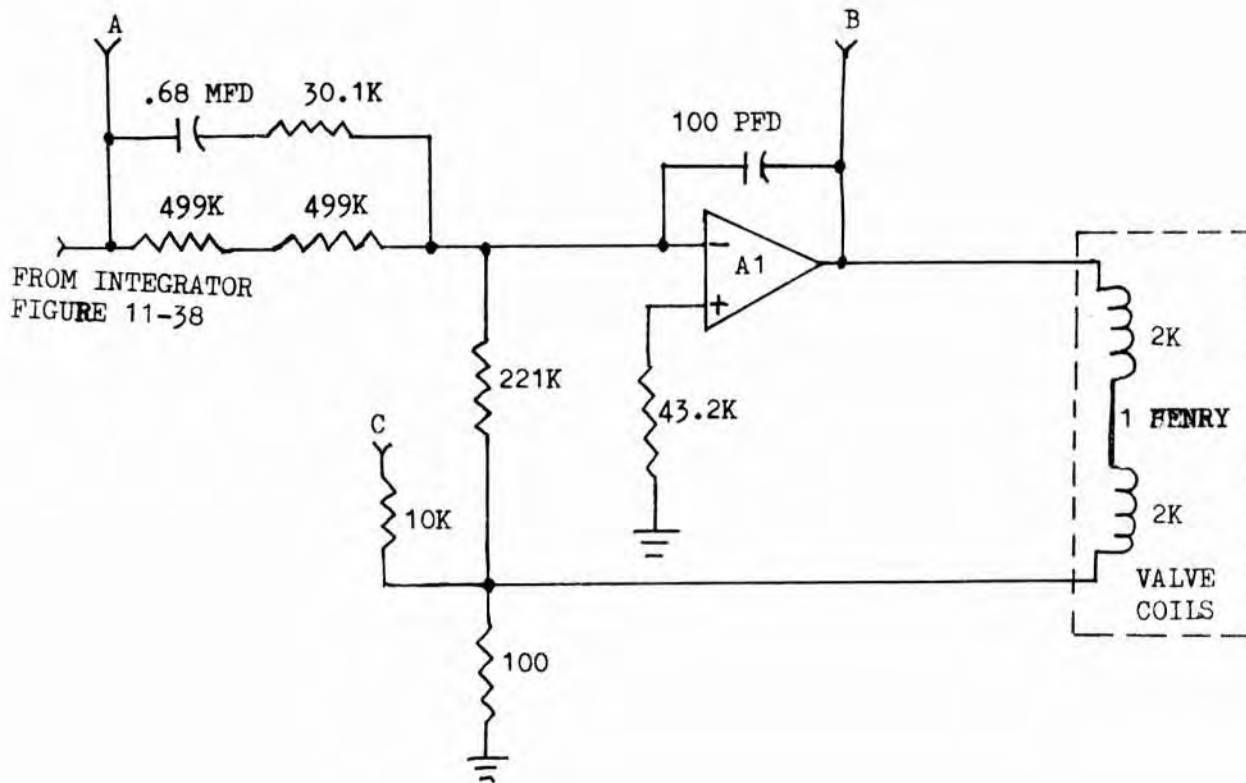


Figure 11-39. Valve Coil Amplifier and Lead Circuit, Schematic Diagram

11-127. ELECTRONIC SWITCH CIRCUIT - The electronic switch (figure 11-40) receives an input voltage proportional to the lift rocket chamber pressure. As this voltage exceeds the preset value established by the trigger adjustment potentiometer the output of amplifier A1 reaches a positive 20.5 volts DC. When the Lunar Sim switch is closed, relay driver transistor Q1 conducts and energizes relays K1 and K2. Relay K2 contact enables the auto throttle motor driver's output stage and magnetic clutch. Relay K1 contacts latch in the relays and enable the T_L/W computer to start computing the weight change due to fuel burnoff. The latch is necessary to ensure Lunar Simulation is not interrupted if the Lift Rocket Pressure drops below the trigger point after start of Lunar Simulation.

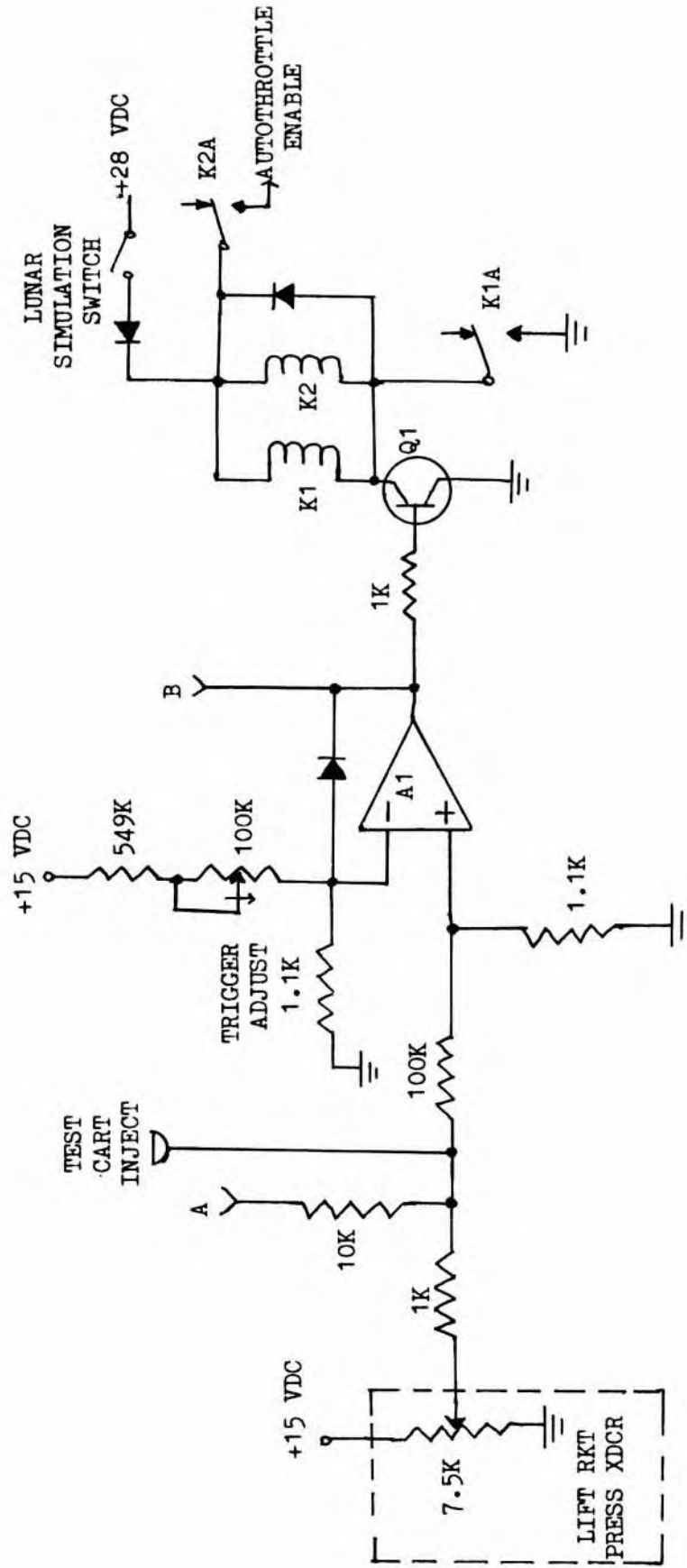


Figure 11-40. Electronic Switch Circuit, Schematic Diagram

11-128. THRUST/WEIGHT COMPUTER CIRCUIT - The JP-4 burnoff weight, is pre-programmed by a fixed input to integrator amplifier, A3, and results in 34.2 lb/min burnoff rate, (figure 11-41). The integrator amplifier's output, TP-E maintained at zero until Lunar Simulation initiation, then relay K1 is energized and the output increases negatively for approximately two minutes at which time it reaches saturation. The hydrogen peroxide weight burnoff is computed by a synchronizer circuit similar to the attitude hold synchronizer in the ACS system. Integrator amplifier, A2 is continuously updated to the peroxide remaining circuit's output until the initiation of Lunar Simulation by the Electronic Switch. At initiation, relay K1 is energized and the equivalent H_2O_2 fuel remaining is stored as a reference on the integrator amplifier A2, output, A22-TP4. Difference amplifier, A1 output, TP-A then represents the change or burnoff of H_2O_2 after relay K1 is energized and hence the H_2O_2 weight loss during Lunar Simulation flight. The lift thrust and combined weights are applied to a solid state divider circuit to generate the acceleration caused by the lift rocket thrust.

11-129. The divider (figure 11-42) operates as follows: amplifier A1 is a standard differential amplifier except a voltage controlled resistor (field-effect transistor) is added in series with the feedback resistor. The field-effect transistor, SU-412, has a drain to source resistance, R_{DS} , which can be varied from 400 to 4000 ohms quite accurately by controlling the gate to source voltage, V_{GS} . A matched field-effect transistor is included as part of an input bias network to amplifier A2, whose output becomes a function of V_2 . Assume a positive voltage, V_2 , creates input current i_2 to amplifier A2. The amplifier will then adjust its output voltage until the negative bias current flowing through the SU-412 transistor equals i_2 .

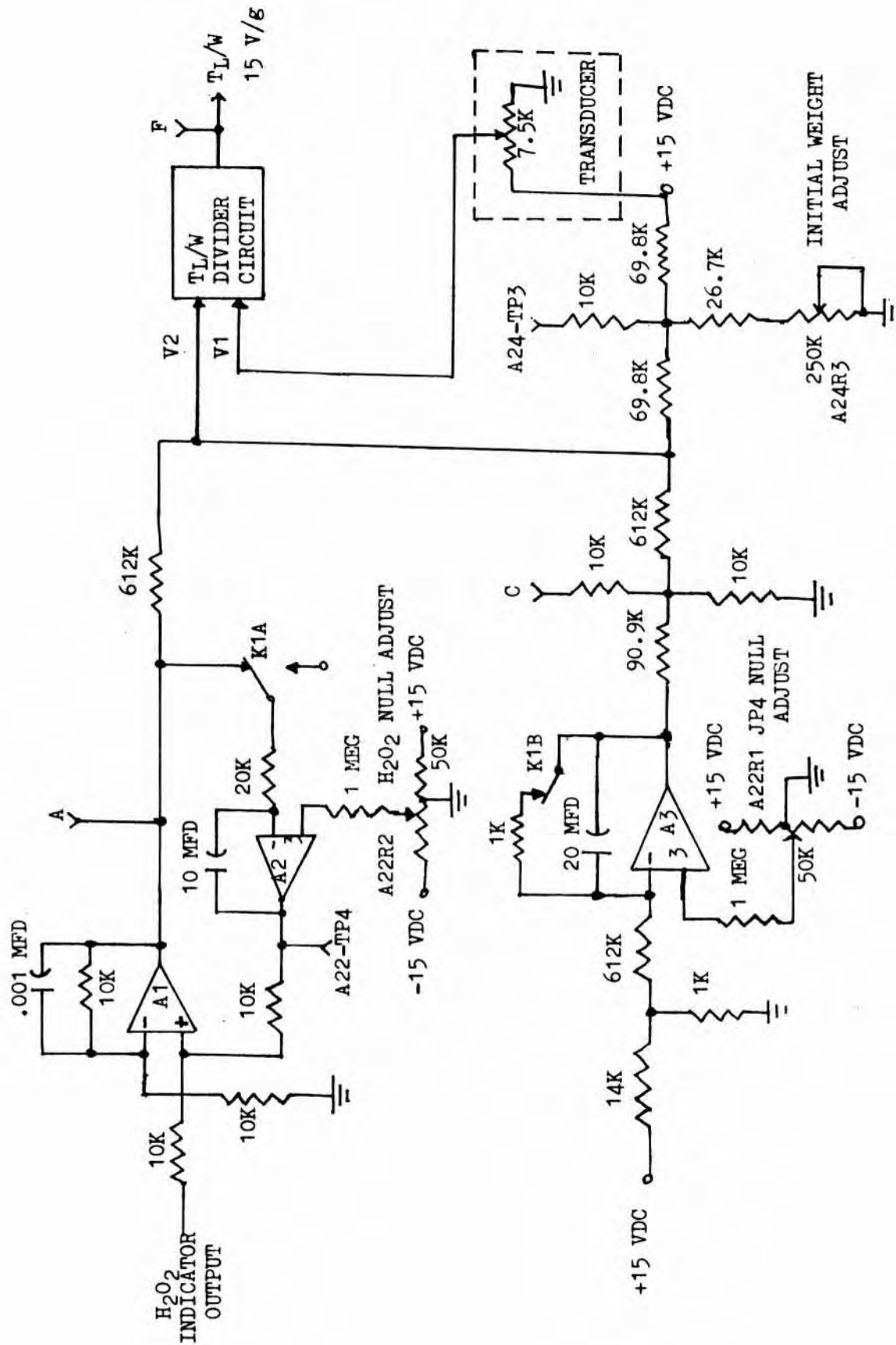


Figure 11-41. Thrust/Weight Computer Circuit, Schematic Diagram

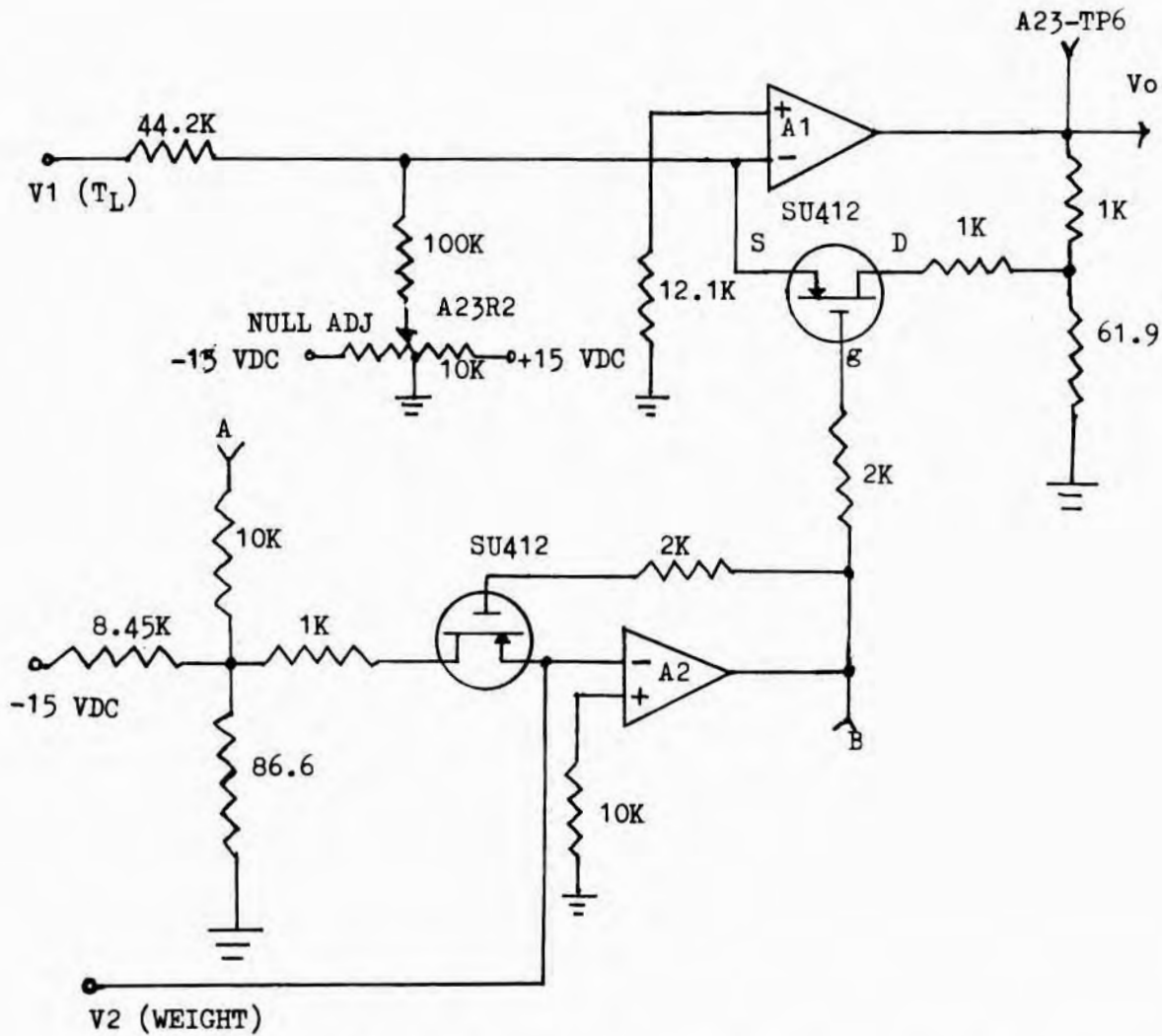


Figure 11-42. Thrust/Weight Computer Divider Circuit, Schematic Diagram

11-130. BODY AXIS ERROR AMPLIFIER CIRCUIT - The X-, Y-, and Z- axis error amplifiers are very similar in circuit design. The X- and Y-, and Z- error amplifiers are so similar that figure 11-43 represents both. Figure 11-44 is the schematic for the Z-axis error amplifier. The axis linear accelerometer signals and the vertical gyro resolver signal are summed by the axis error amplifier for each axis (X, Y, and Z) amplifier. During Lunar Simulation this error signal is used to position the axis (X, Y) thrust vector to compensate for drag along that axis. The

accelerometer signals TP-A and TP-B are summed together to compensate for rotational vehicle accelerations and allows for only linear translational accelerations. The X-axis horizontal vertical gyro with resolver pick-offs has a 400-hertz output scaled for $5/6g \sin \theta$. The Y-axis horizontal resolver gyro command is $5/6g \cos \theta \sin \phi$ since roll is on the inner gimbal and requires one more resolution than pitch. In addition the Y-axis 400-hertz is scaled for $7.71 \frac{vdc}{g}$ which requires different filter components. The X-axis output is scaled for $33.2 \frac{vdc}{ge}$. The error amplifier signal is then modulated at 400-hertz and sent through a 400-hertz bandpass filter. The bandpass filter shapes the square wave signal to a 400-hertz sine wave output at TP-G. It is necessary to change the DC error signal to an AC voltage in order to couple it through the gimbal resolvers. For ground testing of the Lunar Simulation Loop, relay K1 is energized and a jet engine gimbal potentiometer signal is fed back to the summing amplifier, since the jet engine thrust is not able to couple back through the accelerometers. A null adjustment potentiometer is also included to compensate for amplifier and input signal offsets. The Y-axis amplifier has the gimbal angle potentiometer output fed back to the inverting rather than the non-inverting input of the summing amplifier. This is necessary because the signal phasing in the engine channel differs in the pitch and roll axis.

11-131. The Z-axis (vertical) error amplifier (figure 11-44) sums the two Z-axis linear accelerometer signals, the vertical gyro signal and the thrust/weight computer (lift rocket acceleration) signal, and generates an acceleration error with respect to the vehicle's Z body axis. During Lunar Simulation this error signal is used to adjust the Z-axis thrust to cancel $5/6$ of the earth's gravity and simulate a $1/6$ gravity field (lunar gravity). The Z accelerometer signals, TP-B and C, are summed together, which compensates for rotational vehicle accelerations, but allow only linear translational Z axis accelerations to be summed. The vertical gyro

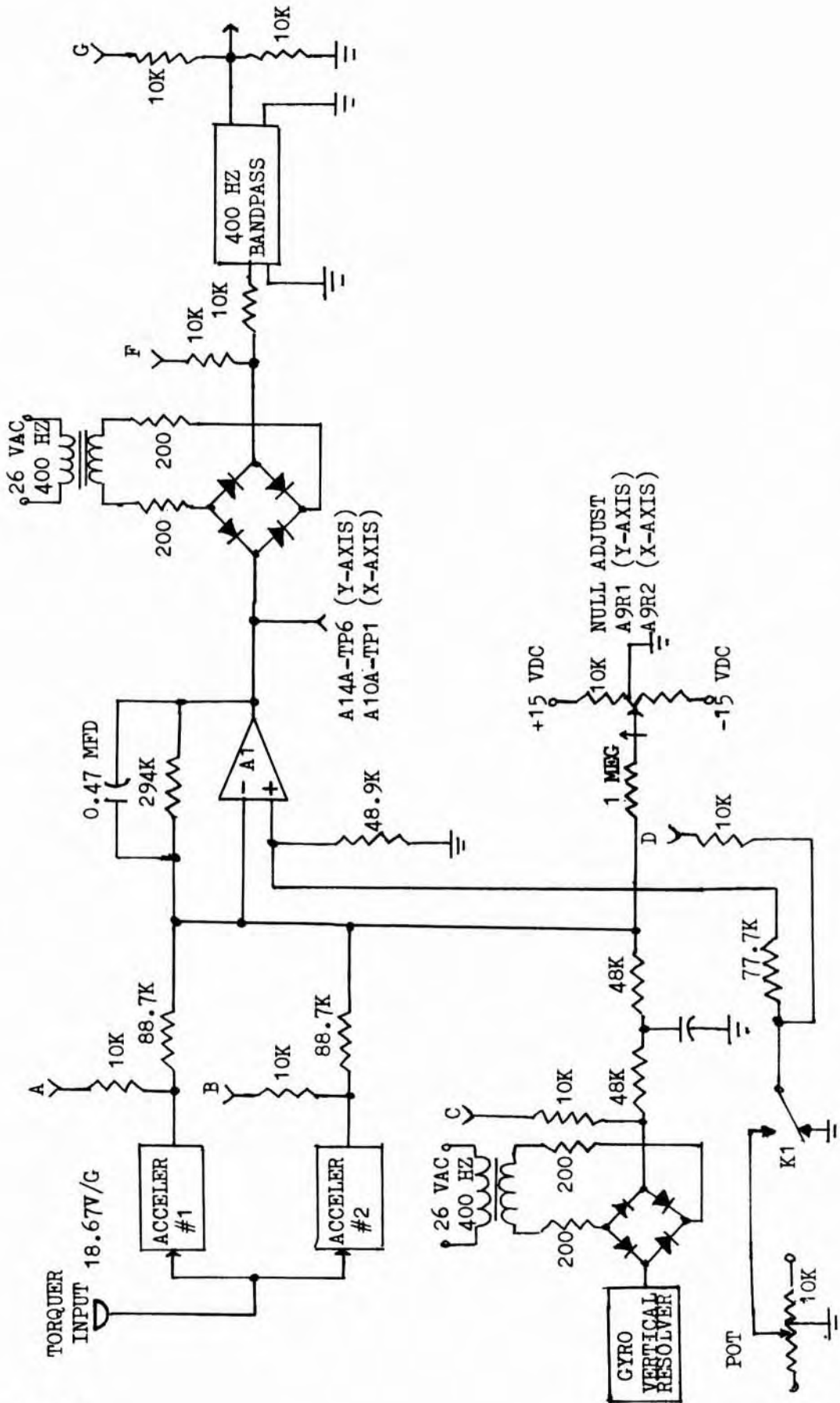


Figure 11-43. Body Axis Error Amplifier Circuit, Schematic Diagram

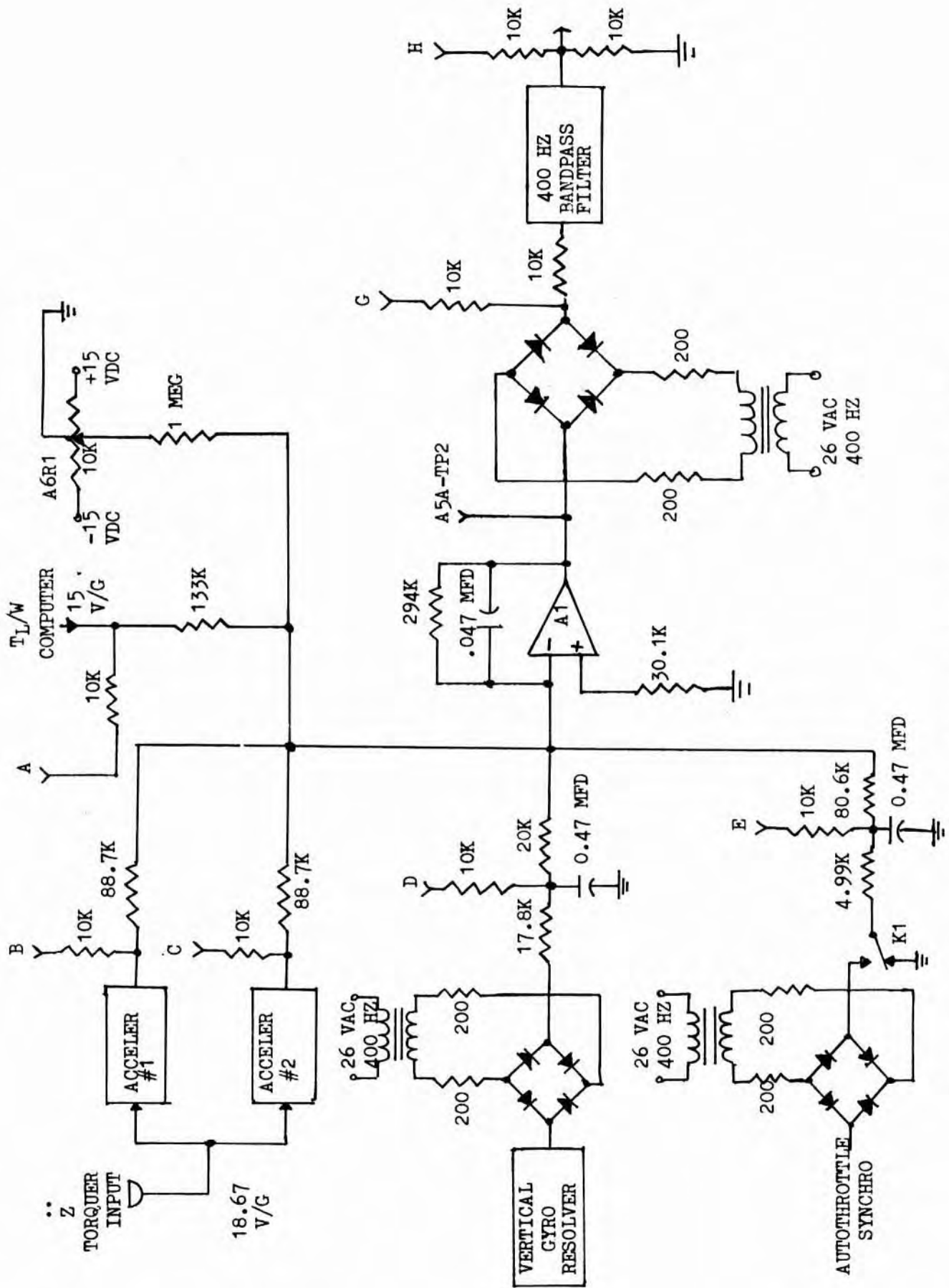


Figure 11-44. Z-Axis Error Amplifier Circuit, Schematic Diagram

400-hertz signal is scaled for $5/6 g \cos \theta \cos \phi$. This signal is applied to a phase-sensitive demodulator and filtered. The output of the error amplifier, A5A-TP2, is scaled for $33.2 \frac{\text{vdc}}{g_e}$. The error signal is modulated at 400-hertz, sent through a 400-hertz bandpass filter and applied to the gimbal resolvers. The bandpass filter shapes the square wave signal into a 400-hertz sine-wave output at TP-H. For ground testing of the Lunar Simulation Loop, relay K1 is energized and the auto throttle feedback synchro is phase-sensitive demodulated, filtered, and fed back to the summing amplifier. This is done since the jet engine thrust is not able to couple back through the Z-accelerometers while ground or hangar testing. A null adjustment potentiometer is included to compensate for amplifier and input signal offsets.

11-132. THRUST/WEIGHT INDICATOR AMPLIFIER - The thrust/weight indicator amplifier circuit (figure 11-45) monitors the Z-axis accelerometers and provides an output to the telemetry and instrumentation system and drives the potentiometric thrust/weight indicator. The accelerometer signals are summed to produce a telemetry signal at the output of amplifier A1, TP-A, with a scale factor of 6.67 vdc/g, which is applied to amplifier A2 whose input has a fixed bias. This bias converts the 1g accelerometer signal to $1/6 g$ at the output of amplifier, A2. Therefore during a hover or while sitting on the ground the thrust/weight indicator will indicate 1g (lunar) and amplifier A2 output, TP-B, will be positive 1.1 volts DC. The rate of change about this point at TO-B will be 6.67 V/g.

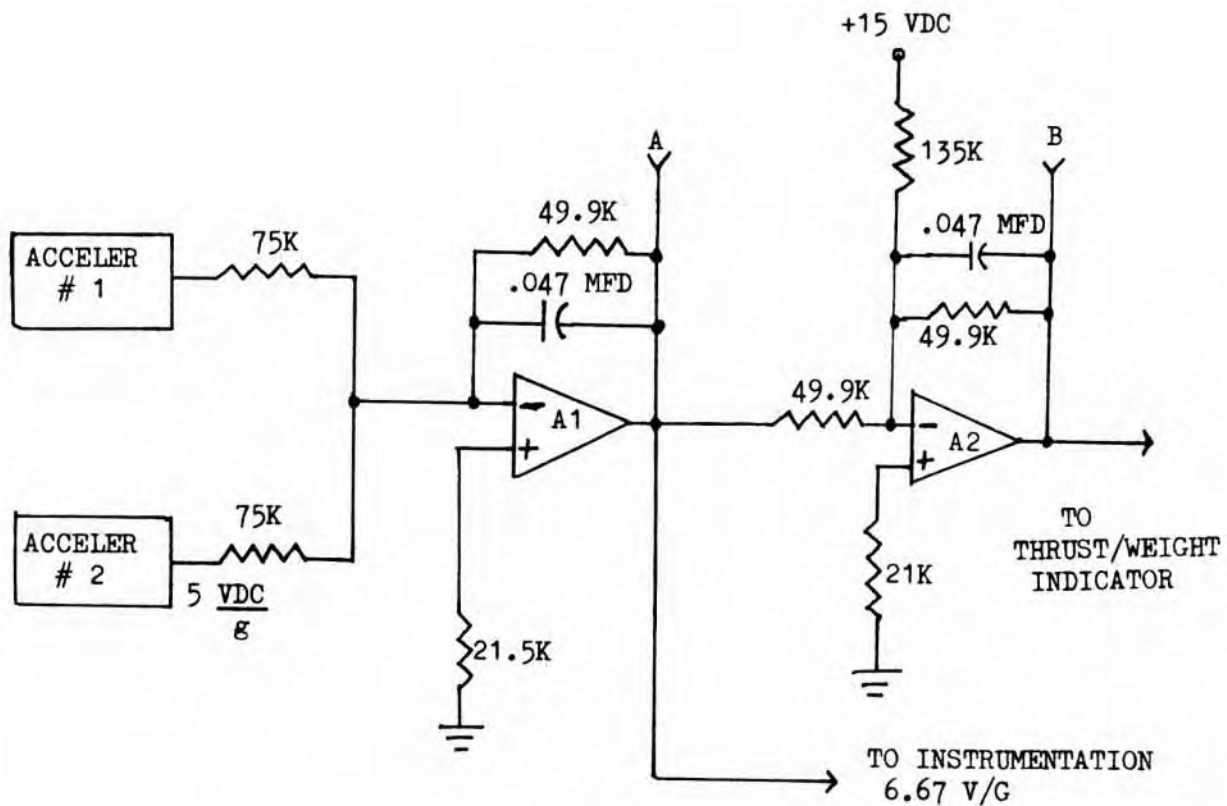


Figure 11-45. Thrust/Weight Indicator Amplifier Circuit, Schematic Diagram

11-133. BOOSTER AMP AND RESOLUTION CIRCUIT - The booster amp and resolution circuit (figure 11-46) converts the three-body axis acceleration errors to three jet engine axis acceleration error signals. The errors in the X and Y axis (\ddot{X}_{JE} and \ddot{Y}_{JE}) drive the pitch and roll jet stabilization systems respectively. The Z axis error (\ddot{Z}_{JE}) is coupled to the auto throttle control system to adjust the engine thrust magnitude. Four identical booster amps (two per package) are used as driving amplifiers for the temperature compensated gimbal resolvers. The transfer function of this resolver chain is as follows:

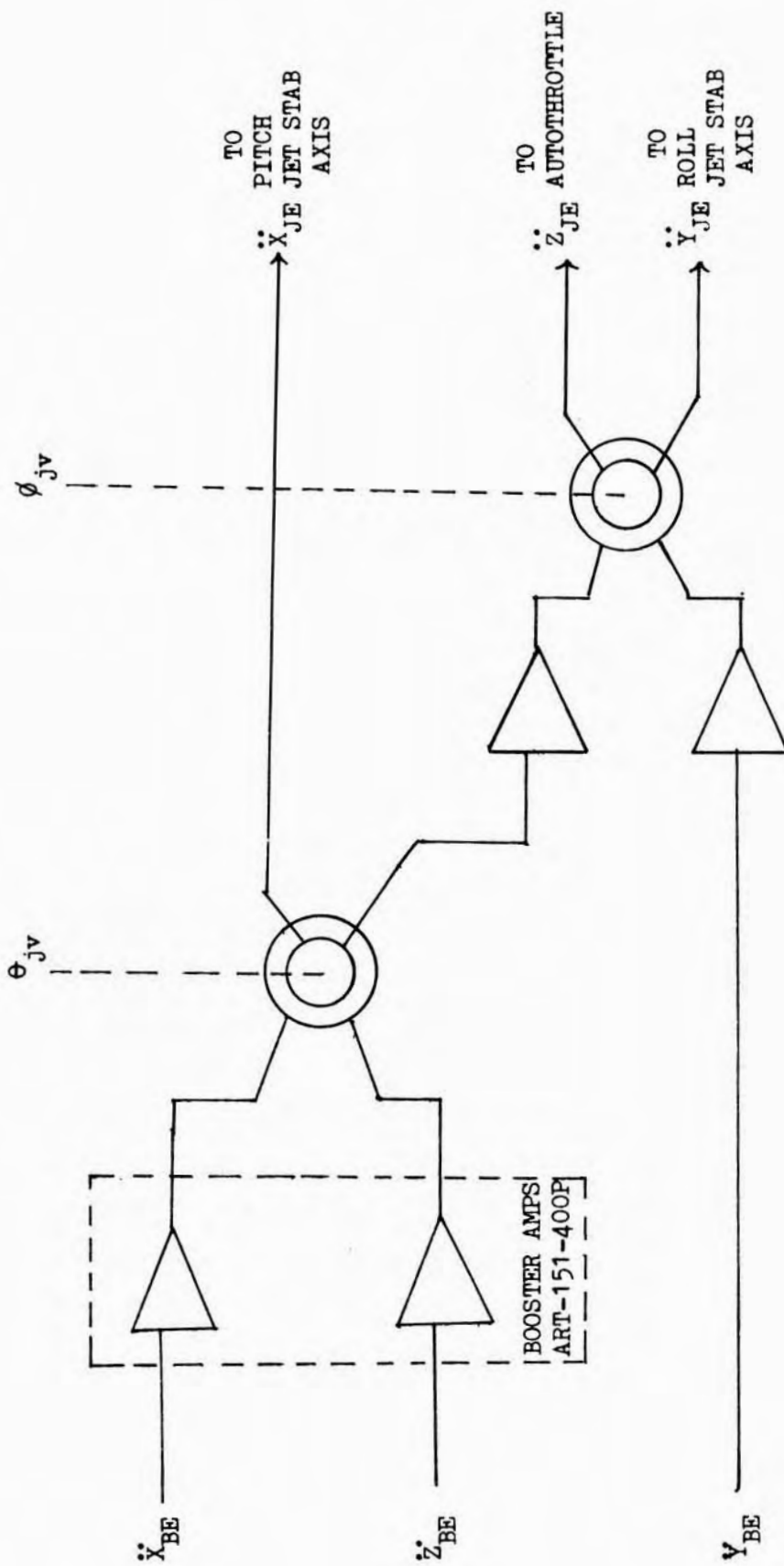


Figure 11-46. Booster Amplifier and Resolver Circuit, Block Diagram

$$\ddot{X}_{JE} = \ddot{X}_{BE} \cos\theta + \ddot{Z}_{BE} \sin\theta$$

$$\ddot{Z}_{JE} = -\ddot{X}_{BE} \sin\theta \cos\phi - \ddot{Y}_{BE} + \ddot{Z}_{BE} \cos\theta \cos\phi$$

$$\ddot{Y}_{JE} = \ddot{X}_{BE} \sin\theta \sin\phi + \ddot{Y}_{BE} \cos\phi - \ddot{Z}_{BE} \cos\theta \sin\phi$$

11-134. AUTO THROTTLE CHANNEL CIRCUITS - The auto throttle channel (figure 11-47) provides a signal to drive the two-phase, 400-hertz rotary auto throttle actuator motor to the desired position. The channel has two modes of operation: (1) the Lunar Simulation mode and (2) the Emergency Throttle mode. In the Lunar Simulation mode a Z-channel acceleration error is applied at the input, TP-A, and is fed to the auto throttle motor control phase with an AC gain of 3500. The output amplifier signal is coupled to the motor through the limit switch circuit relays during Lunar Simulation mode. During Emergency Throttle operation relays K1 and K2 are energized, the throttle command synchro signal is applied at TP-A, and the auto throttle feedback synchro signal is applied at TP-B. The remainder of the electronics used is the same as during Lunar Simulation, except relay contact K2A couples the output amplifier to the servo motor directly, therefore bypassing the limit switches.

11-135. The selected signal or signals, dependent upon mode of operation, is amplified, demodulated and filtered. A one-microfarad capacitor forms a lead term to compensate the auto throttle servo loop. Amplifier A1 is a DC differential amplifier and provides unity DC gain for the filtered demodulator signal and then applies it to another R-C filter before modulating the signal at 400-hertz (TP-F). The modulator output is applied to a 90 degree R-C phase shift network in order to provide a correctly-phased signal for the two-phase servo motor. The output of the phase shifter, TP-G, is amplified with an AC gain of 71 and then applied

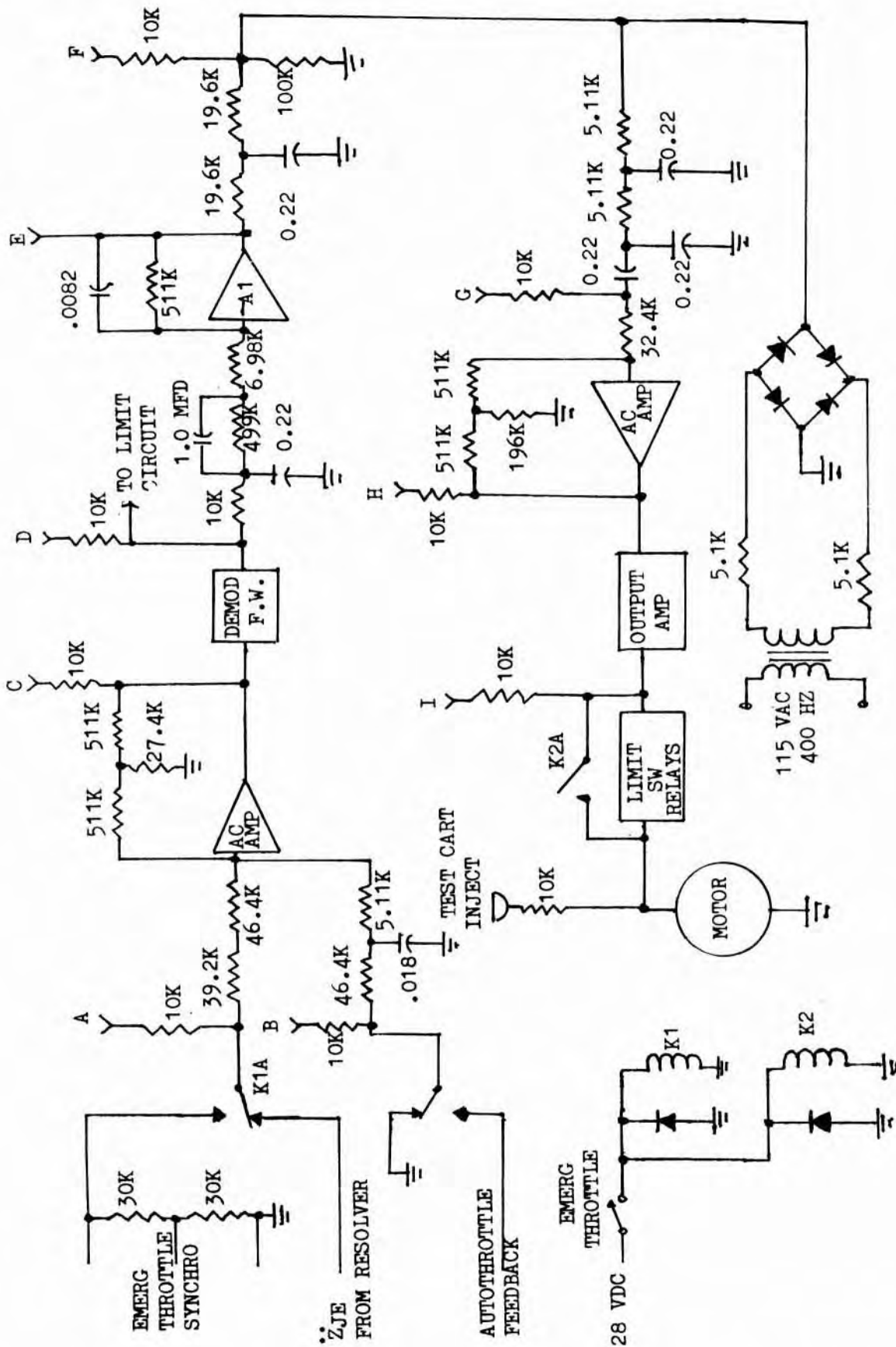


Figure 11-47. AutoThrottle Channel Circuits, Schematic Diagram

to the Output Driver Amplifier. The driver amplifier is a class-B power amplifier which has a tuned transformer output, TP-I, which couples it to the servo motor control phase winding.

11-136. LIMIT SWITCH CIRCUIT - The limit switch circuit (figure 11-48) is designed to interrupt the auto throttle motor voltage signal whenever the throttle drives too far forward or backward, and allows the throttle to drive back into the accepted region when the drive signal is of the correct polarity. For circuit analysis, assume the throttle is driving backward, then the voltage at TP-A is negative and transistor Q1 is cut-off. When the throttle is in the acceptable region, both K1 and K2 are de-energized. When the throttle engages the aft limit switch, relay K1 will be driven by transistor Q2 and relay contact K1A will cutoff the motor voltage. When the drive signal reverses, and the voltage at TP-A increases above approximately positive 2.15 volts DC transistor Q1 will turn ON and therefore cutoff Q2 and de-energize relay K1. This allows the motor to run forward out of the aft limit switch.

11-137. Next assume the throttle drives into the forward limit switch and engages relay K2. Relay contact K2A interrupts the motor voltage, and relay contact K2B puts positive 28 volts DC at TP-B and turns on transistor Q1 which keeps Q2 cutoff. When the drive signal reverses and attains a magnitude greater than negative 2.15 volts DC at TP-A transistor Q1 turns OFF, Q2 turns ON, and relay K1 is energized. Relay K1 and K2 now are energized and the throttle drives aft out of the limit. As the forward limit switch opens both relays K1 and K2 de-energize and allow the motor to continue driving.

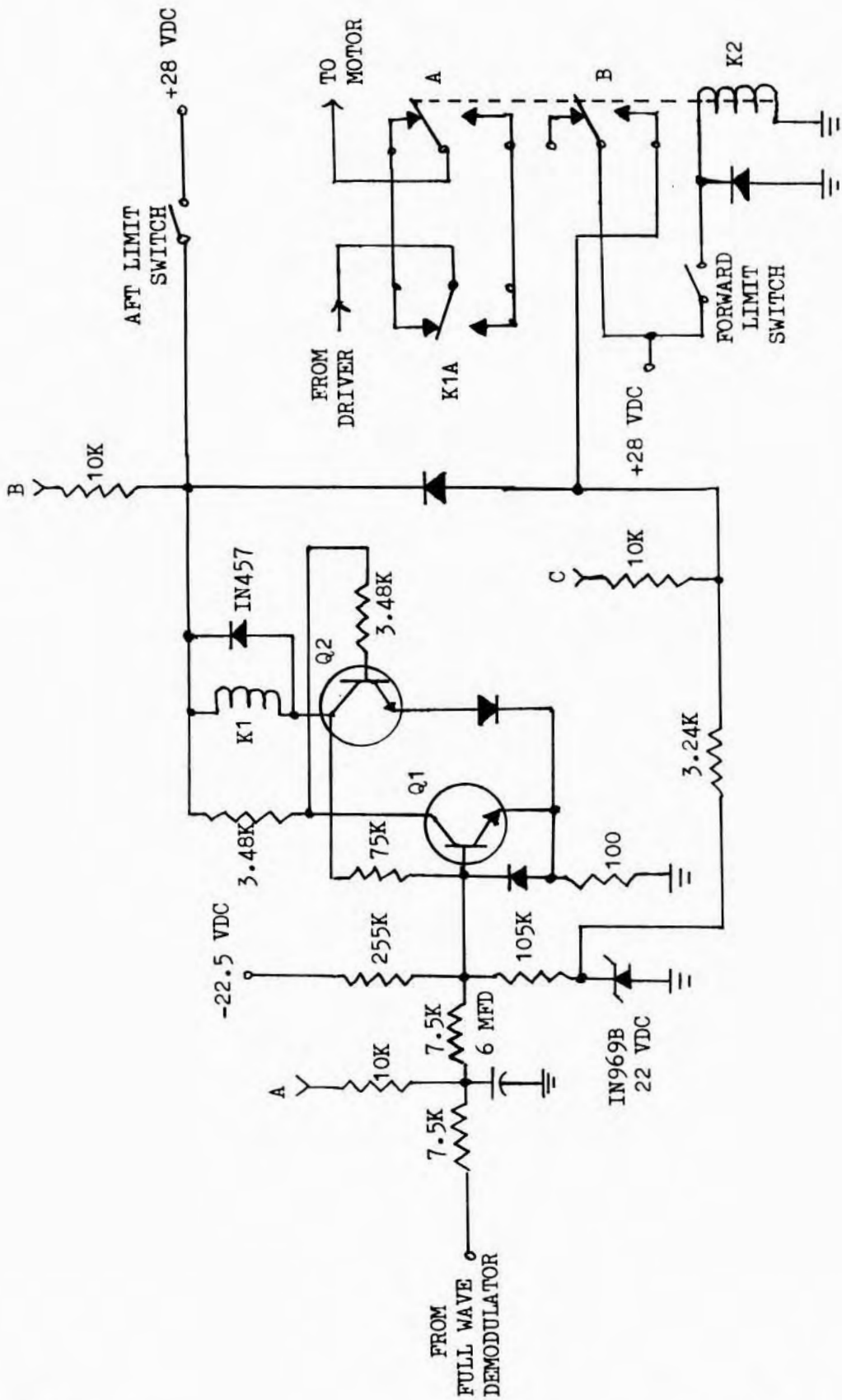


Figure 11-48. Limit Switch Circuit, Schematic Diagram

11-138. OPERATIONAL CHECKOUT

11-139. An operational checkout of the avionics system is performed by following the procedures provided in the Avionic System Preflight Checkout with Checkout Cart, Checklist Number 7260-931006. An alternate checkout can be performed by following the procedures provided in the Avionic System Manual Preflight Checkout, Checklist Number 7260-931018.

11-140. SYSTEM TROUBLESHOOTING

11-141. Avionics system troubleshooting is performed by following the procedures provided in the Avionics System Hangar Ground Test Procedures, Report Number 7260-928050.

11-142. REMOVAL PROCEDURES

11-143. The removal procedures are provided for the avionics system electronic units and the hand controller assembly in paragraphs 11-144 through 11-147.

11-144. AVIONICS ELECTRONIC UNITS

11-145. The removal of the avionics system electronic units is performed by following the general procedure:

CAUTION

Ensure power has been off for at least
two hours before disconnecting the
attitude gyro unit.

- A. Cut and remove safety wire.
- B. Disconnect electrical connectors.
- C. Loosen front and rear mounting retainers.
- D. Remove unit from mounting rack.

CAUTION

During removal, installation and handling of electronic units, do not drop, bump or otherwise damage these delicate electronic units.

11-146. HAND CONTROLLER REMOVAL

11-147. To remove the hand controller, proceed as follows:

- A. Remove plexiglas cover from hand controller grip.
- B. Remove six bolts and remove cover from hand controller mounting pedestal.
- C. Remove four washer-head screws from hand controller mounting pedestal.
- D. Disconnect the electrical connections, tag and identify and remove hand controller.

11-148. INSTALLATION PROCEDURES

11-149. Installation of the avionics system electrical units and the hand controller is performed in reverse order of removal.

11-150 ADJUSTMENTS

11-151 The step-by-step procedures and test equipment required for adjustment of the avionics system are provided in paragraphs 11-152 through 11-175, and table 11-4. Adjustments after component replacement are provided in paragraphs 11-176 through 11-211.

11-152 TEST EQUIPMENT

11-153 The following test equipment is required for adjustment of the avionics system.

- A. Test Cart, P/N 7260-703001-1
- B. Rate Table
- C. Angle Indicator Table

11-154 STEP-BY-STEP PROCEDURES

11-155 Adjustment of the avionics system is performed by following the general procedure outlined and by referring to table 11-4 for each circuit. The general procedure is for circuits in primary, monitor, backup channels and special circuits. Differences between channels are noted in text and table 11-4.

11-156 RATE COMMAND ADJUSTMENT - The adjustment of this circuit consists of setting the gain and null potentiometers. The two adjustments must be made together, since they interact when hand controller offsets are present. The procedure is as follows: with the hand controller at null, adjust the null potentiometer for a minimum output. Next, fix the hand controller at ten degrees (full throw) and adjust the gain potentiometer for 10.00 volts, dc. Return the hand controller to null and rezero the output by using the null adjust potentiometer. Fix the hand controller at ten degrees and readjust the gain potentiometer for 10.00 volts, dc.

Return the hand controller to null and note the output. Fix the hand controller at ten degrees in the opposite direction to that moved before and let it return to null; note the output. This output will be different since the hand controller has mechanical hysteresis. Adjust the null potentiometer such that voltages are equal, but of opposite polarity. Finally recheck and balance the output voltage for maximum positive and negative hand controller commands. Typical values of offset voltage range from 2 to 50 millivolts, dc. The specific adjustment potentiometers and test points are listed in table 11-4, items 1, 4, 7, 9, 24 and 26.

11-157 RATE GYRO FEEDBACK ADJUSTMENT - The adjustment of this circuit consists of setting the gain and null potentiometers. The two adjustments must be made together, since they interact when hand controller offsets exist. The procedure is as follows: with the rate gyro on a rate table and at null, adjust the null potentiometer for a minimum output. Next, rotate the gyro at 20 degrees per second (maximum input) and adjust the gain potentiometer for 10.00 volts, dc. Return the rate gyro to a still condition and readjust the null potentiometer. Rotate the gyro at 20 degrees per second again and reset the gain for 10 volts, dc. Return the rate gyro to a still condition and note the null voltage. Rotate the gyro in the opposite direction at 20 degrees per second and let it return to a still condition; note the output voltage. This null output will be different than before since the rate gyro possesses hysteresis and striction. Adjust the null potentiometer such that voltages are equal, but of opposite polarity. Finally recheck and balance the output voltage for 20 degrees per second clockwise and counter-clockwise rate gyro rotations. Typical values of offset voltage range from 10 to 80 millivolts, dc. The specific adjustment potentiometers and test points are listed in table 11-4, items 2,5,8, 10, 25 and 27.

11-158 ATTITUDE GYRO FEEDBACK ADJUSTMENT - The adjustment of this circuit consists of setting the gain and null potentiometers. The two adjustments must be made together, since they interact when attitude gyro offsets exist. The procedure is as follows: with the attitude gyro on a level tilt table, adjust the null potentiometer for a minimum output. Next rotate the table to 40 degrees and adjust the gain potentiometer for 8 volts, dc. Return the table to level and readjust for a minimum using the null potentiometer. There is no appreciable hysteresis in the vertical gyro output and, therefore, no attempt is made to bracket or balance the null signal. The specific adjustment potentiometers and test points are listed in table 11-4, items 3 and 6.

11-159 YAW ATTITUDE GYRO ADJUSTMENT - The adjustment of this circuit consists of setting the gain and null potentiometers. The two adjustments must be made together since they interact when directional gyro or CDX offsets exist. The procedure is as follows: with the gyro on a table with calibrated heading indications, adjust the gyro until an in-phase null is obtained at the gain potentiometer arm. This can be accomplished by using a Phase Angle Voltmeter. Note the table's heading angle and adjust the null potentiometer for a minimum DC output voltage. Next, rotate the table 40 degrees clockwise from the table heading angle noted above and adjust the gain potentiometer to obtain 6.55 volts, dc. Return the table to the original heading angle and readjust for a minimum output using the null potentiometer. There is no appreciable hysteresis in the directional gyro output and, therefore, no attempt is made to bracket or balance the null signal. The specific potentiometers and test points are listed in table 11-4, items 3 and 6.

11-160 THRESHOLD AMPLIFIER ADJUSTMENT - Circuit adjustment consists of (1) setting the two threshold adjustment potentiometers and (2) setting the primary to monitor assist adjustment potentiometer in the monitor threshold amplifier. To adjust the thresholds the ACS system should be

in the Direct-No Model mode to avoid offsets from the hand controller or feedback gyro channels. Monitor the shreshold amplifier output on an oscilloscope, inject a positive voltage equivalent to the desired threshold at the test cart inject input, and adjust the negative output threshold adjustment potentiometer until it just turns the amplifier from OFF to ON. Reverse the inject voltage polarity and similarly adjust the positive output threshold adjustment potentiometer. After potentiometer adjustment, the setting should be checked by injecting an increasing voltage at the test cart threshold inject input until the amplifier output just turns ON, and then note the value of inject voltage. This voltage should be within 0.1 volts (0.02 deg/sec) of the desired voltage. The specific adjustment potentiometers and test points are listed in table 11-4.

11-161 The monitor channel threshold should be set 0.15 degrees per second more than the primary channel to ensure that the monitor channel threshold amplifier does not turn on first, but is instead forced on by the Primary to Monitor Assist circuit. This sequence of switching is necessary since the monitor amplifier has no means of forcing the primary channel amplifier on. The assist adjustment potentiometer is adjusted after the monitor channel threshold has been set. First note the monitor channel threshold with no assist. Turn ON the primary threshold amplifier and measure the monitor threshold again. The difference is the amount of assist and can be changed by varying the 22 turn-500-kilohm assist adjustment potentiometer. The specific adjustment potentiometers and test points are listed in table 11-4, items 11, 12, 13 and 28.

11-162 ATTITUDE HOLD AND SYNCHRONIZER ADJUSTMENT - Adjustment of this circuit consists of (1) nulling the attitude reference integrator, A2, drift and (2) setting the attitude threshold. Nulling the attitude reference drift is accomplished by monitoring the signal during an attitude hold period (typically ten minutes) and adjusting the 50 kilohm center-tapped potentiometer to cancel the drift. Fifty millivolts (0.28 degrees)

should be an upper limit on the allowable drift over ten minutes. The attitude threshold potentiometer is adjusted with the ACS system in Rate-No Model mode with the stick and rate amplifier outputs grounded to avoid null offsets. While in attitude hold, inject a total attitude signal to establish the required degrees of attitude threshold. While maintaining this voltage, adjust the rate/attitude ratio potentiometer so the threshold amplifier, A3, output just turns ON. Reverse the inject voltage polarity and check the coltage at TP-A when the threshold amplifier just turns ON; this should be approximately the same amount of equivalent degrees as before. The specific adjustment potentiometers and test points are listed in table 11-4, item 14.

11-163 YAW ATTITUDE HOLD AND SYNCHRONIZER ADJUSTMENT - The adjustment of this circuit consists in nulling the attitude error integrator's, A1, drift and setting the attitude threshold. Nulling the attitude error integrator drift is accomplished by grounding the yaw DC rate amplifier output, monitoring the integrator output during an attitude hold period (typically ten minutes) and adjusting the 50-kilohm center-tapped potentiometer to cancel any existing drift. One volt (0.2 degree) should be an upper limit on the allowable drift for ten minutes. The attitude threshold adjustment potentiometer should be set after the rate threshold has been adjusted, and the ACS system should be in the Rate-No Model mode with the stick DC amplifier's output grounded to avoid null offsets. Means should also be made for quickly switching the DC rate amplifier output to ground as required. The adjustment procedure is to torque the yaw rate gyro to obtain a low rate (about 50 millivolts per second) of attitude error change. Continue to torque until the voltage corresponding to the desired attitude error threshold is obtained; at this time quickly ground the yaw DC rate amplifier, thereby establishing zero input signal to the attitude error integrator and eliminating rate gyro offset contribution to the threshold amplifier. The attitude error should now remain (hold) at the threshold

value long enough to adjust the 22-turn rate/attitude ratio adjustment potentiometer. The potentiometer should be set such that the threshold amplifier just turns ON. If the attitude error voltage drifts during this adjustment, it will be necessary to unground the yaw DC rate amplifier and torque the rate gyro in the direction required to re-establish the desired voltage. Once this voltage is obtained the procedure can proceed as before. The specific adjustment potentiometers and test points are listed in table 11-4, items 14 and 15.

11-164. DIRECT MODEL ADJUSTMENT - This adjustment consists of setting the null adjustment potentiometer to cancel integrator drift and setting the model acceleration potentiometer to attain the desired model rate slope. The null adjustment potentiometer is set by monitoring the model amplifier output for about ten minutes, and adjusting the null potentiometer to cancel the drift voltage. The maximum allowable drift should be 20 millivolts per minute. The model acceleration potentiometer adjustment consists of three steps: (1) adjusting the ± 15 VDC power supplies which energize the functional direct switch, (2) setting the nominal acceleration in the primary and monitor channel individually, and (3) accurately matching the primary and monitor channel model slopes. The last step is extremely important, since lack of matching can cause a nuisance switching to the Backup mode. The first step required adjusting the positive and negative 15 volts applied to the functional direct switches to 15.00 ± 0.10 volts DC. This will enable the model to generate the same model slope for both polarity commands. The second step is performed by putting the model outputs, primary and monitor channel, on a chart recorder, putting in a stick command, and measuring the model signal slope obtained. Then readjust the acceleration potentiometer until the desired value is obtained. The third step is performed by observing the difference between the primary and monitor model outputs and adjusting the monitor channel acceleration adjustment potentiometer

to obtain an average minimum difference for both positive and negative commands. The model signal difference can be displayed directly on a Fluke differential voltmeter or a record can be made by recording the output of a differential amplifier whose inputs are the two model signals. The maximum dynamic difference allowed to exist between the primary and monitor channel models should be 50 millivolts DC (0.1 deg/sec) with full scale model output excursions of 10 volts DC (20 deg/sec). The specific adjustment potentiometers and test points are listed in table 11-4, items 16 and 17.

11-165. MODEL RATE ADJUSTMENT - This adjustment consists of setting the model acceleration potentiometer to attain the desired model rate slope. The null potentiometer is adjusted in the more critical Direct with Model mode. Reference paragraph 11-164. The model acceleration potentiometer adjustment consists of two parts: (1) setting the nominal acceleration in the primary and monitor channel individually and (2) accurately matching the primary and monitor channel. The second step is extremely important since lack of matching can cause a nuisance switching to Backup. The first step is performed by putting the model outputs, primary and monitor channel, on a chart recorder, putting in a stick command, and measuring the model signal slope obtained. Then readjust the acceleration potentiometer until the desired value is obtained. The second step is performed by observing the difference between the primary and monitor model outputs and adjusting the monitor channel acceleration adjustment potentiometer to obtain an average minimum difference for both positive and negative commands. The model signal difference can be displayed directly on a Fluke differential voltmeter or a record can be made by recording the output of a difference amplifier whose inputs are the two model signals. Since four individual, fixed limiter modules are involved (two for amplifier A1 in the primary and two in the monitor channel), and each influence the matching between the channels, it is necessary that the

driver amplifiers, A1, have closely matched limiter modules. The maximum dynamic difference allowed to exist between the primary and monitor channel models should be 100 millivolts DC, (0.4 deg/sec) with full scale model output excursions of 10 volts DC (20 deg/sec). The specific adjustment potentiometers and test points are listed in table 11-4, items 16 and 17.

11-166. MODEL LEAD ADJUSTMENT - The adjustment consists of (1) nulling the offset voltage, and (2) adjusting the time constant potentiometer for the desired initial pulse duration. Since this circuit has a positive temperature drift coefficient, the circuit output voltage is set at approximately -40 millivolts DC with the box tops off; thus after the tops are on and the internal box temperature rises the output voltages stabilize close to zero. The time constant adjustment is performed by monitoring the threshold amplifier's output on an oscilloscope while injecting stick commands. The potentiometer is adjusted to obtain the desired pulse duration. It should be noted that this pulse is the rocket solenoid command signal and the effective rocket firing pulse will be less due to rocket system delays; in addition a minimum firing command time of thirty milliseconds is necessary to obtain any rocket response. The specific adjustment potentiometers and test points are listed in table 11-4, items 18 and 19.

11-167. ATTITUDE SYNCHRONIZER RATE SWITCH ADJUSTMENT - The adjustment is performed by monitoring the output voltage rotating the rate gyro at the desired rate, and setting the trigger adjustment potentiometer until the output voltage switches to positive 28 volts DC. The specific adjustment potentiometers and test points are listed in table 11-4, items 20 and 29.