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PAPER 4.4

STABILIZATION, POINTING AND COMMAND CONTROL OF A BALLOON-BORNE 1-METER TELESCOPE

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ABSTRACT

A 1-meter balloon-borne telescope has been constructed and flown to observe far-infrared radiation from celestial sources. The attitude control systems must perform to the diffraction limit of the telescope (<0.5 arcmin.) for stabilization and have positioning capability for source acquisition. These and associated systems are discussed in detail, as is the command control of the payload as a whole.

INTRODUCTION

The attitude control requirements for the 1-meter telescope balloon gondola developed by the Harvard College Observatory, the Smithsonian Astrophysical Observatory and the University of Arizona (Fazio et al, 1974; Hazen, 1974) are that the telescope line of sight be pointed in the celestial sphere to an accuracy of 0.1 degrees and then stabilized to track the observed object with rms errors below 0.5 arcmin. and DC drift of less than 1 arcmin./minute. These requirements are achieved in an altitude-azimuth mounting utilizing DC torquers and position servos. Figure 1 is a general view of the telescope and gondola.

For the elevation control system the reaction mass is the gondola frame; in azimuth it is a heavy reaction wheel. The azimuth reference for initial positioning (position mode) is a servo-driven null magnetometer which always points to the local north. The elevation reference is the gondola vertical. For tracking stabilization (inertial mode) the control signals are derived from a pair of inertial gyros mounted on the telescope base ring. By switching appropriate DC currents to the gyro torquers, large (1.5 X 3 degrees) or small (0.5 X 1.0 degrees) rasters can be executed over the target area. Either gyro can also be torqued by manual command from the ground, thereby performing straight-line scans at rates of 1 degree or 3 degrees/minute. Figure 2 depicts the principal gondola sub-systems in block diagram form.

In addition to the positioning requirements, the design of the control systems must be able to accommodate the oscillatory periods characteristic of balloon suspended payloads (Frecker, 1968; Nidey, 1968). For our payload these include a simple pendulum period of approximately 20 seconds, a compound pendulum period of about 2 seconds, a suspension train torsional period of about 40 seconds, and a maximum balloon rotation rate of 1 revolution per minute.

A payload which is actively controlled in real time from the ground requires a versatile and reliable command capability. This is achieved by using the relatively simple command interface (provided by NCAR) to enter a command matrix, thus providing many more functions with some redundancy.

Each of these areas is described in detail in the following sections.

AZIMUTH CONTROL SYSTEM

The azimuth system achieves its control by torquing a 20 slug-foot^2 reaction wheel with respect to the gondola frame. The gearless DC torque motor is an Inland type T-7203 rated at 22 foot-pounds. A system block diagram is shown in Figure 3. It can be seen that the acquisition (position mode) and tracking (inertial mode) loops are completely independent except for the torque motor and its power amplifier.

The position mode reference is derived from the servo magnetometer, an independent servo system that is used to stabilize a table with respect to magnetic north using a null magnetometer (Schonstedt MND-5) as the sensing element. A 13-bit absolute position encoder reads the orientation of the gondola with respect to the magnetometer table and, with suitable correction, with respect to geomagnetic north. A digital subtraction is then performed between the encoder output and a 13-bit position command telemetered from the ground. This subtraction provides the input signal for a D-A converter whose output is the azimuth position error signal. To avoid high rate transients, a rate limiter has been added that uses a clock and the 13-bit command word as inputs and whose output is a 13-bit word that changes at the clock rate (1/2 degree/second) to adjust itself to equal the command word. Thus, when a new azimuth angle is commanded, the error signal is changed at a rate that the servo systems can follow. An addition to the rate limiter compares the difference between the output and input 13-bit words and if this difference is greater than 180° causes the payload to take the shorter path to the new azimuth angle. For increased sensitivity, the D-A converter is of 10-bit capacity and is biased to mid-range so as to avoid a discontinuity at zero error.

The inertial mode reference is a rate-integrating gyro (King C702519007) mounted on the telescope base ring. (The gyro is caged in the position mode and is thus an independent rate sensor in this mode.) This mounting is a complicating factor in that the azimuth gyro sensitivity is reduced by the cosine of the elevation angle. In order to compensate for this effect, the output of the azimuth gyro synchronous demodulator is impressed across a nonlinear pot ganged with the elevation position pot, which has a transfer function of 0.2 secant θ_{EL} for θ_{EL} between 0° and $\pm$ 75°

and the output of this pot is fed to the gyro loop compensation amplifier. The advantage of the gyro mounting is that it provides direct control of the telescope line of sight. The disadvantage is that at higher elevation angles the gyro is increasingly sensitive to payload roll, and with an imperfectly aligned reaction wheel axis induces compound pendulum oscillations. The problem is kept under control by the friction damping in the payload support joint (Figure 4) at elevation angles below 40° . Here, a gimballed three axis (i.e. cross-elevation) mount would have been advantageous but was not used because of cost limitations (Frecker, 1968).

Both position and inertial modes utilize type 2 loops (1 kinematic, 1 electronic integration) and both have output velocity feedback via a 1.20 volts/radian/second tachometer mounted on the reaction wheel drive shaft. In position mode the system has a calculated bandwidth of 4.8 radians/second, while in inertial mode the bandwidth is about 1 radian/second. Reduced block diagrams for the azimuth system when operating in position and inertial modes are shown in Figures 5A and 5B respectively. A Bode plot showing the system response in the two modes is depicted in Figure 6.

MOMENTUM DUMP SYSTEM

Not discussed in the foregoing section was the need to maintain long term control of the reaction wheel angular velocity in spite of wind disturbances and balloon rotation influencing the azimuth system. The momentum dump system accomplishes this by coupling momentum from the gondola into the balloon when the reaction wheel velocity exceeds $\pm$ 1 radian/second, performing that function by alternately torquing the gondola clockwise and counterclockwise against the balloon shroud lines with a duty cycle determined by the azimuth reaction wheel velocity. The momentum dump motor is a Globe type BL DC motor with an integral gearhead which drives a ring gear attached to the periphery of the main payload support bearing. This bearing has a running friction level of 4 foot pounds under load, and breakaway is assured by means of an inertia bar mounted on the link above the payload support shaft.

As shown in the block diagram contained in Figure 3, the motor is driven continually by a 5 Hz oscillator, causing it to reverse direction twice every 0.2 seconds. When the reaction wheel velocity exceeds 1 radian/second the output of the reaction wheel tachometer is added algebraically to the output of the 5 Hz oscillator, causing the duty cycle to change. The result is a net torque between the gondola and the shroud lines in a direction such that the reaction wheel velocity is reduced. A reduced block diagram is shown in Figure 7.

Figure 8 shows the relationship between momentum dump motor velocity and bearing torque, from which it can be seen that:

$$\dot{\theta}_{md} = (\sin 31\ t) + 7.2\ \dot{\theta}_w$$

where $\dot{\theta}_{md}$ is motor shaft velocity in radians/second and $\dot{\theta}_w$ is reaction wheel velocity in radians/second.
Torque reversals occur at times t_r, given by

$$168 \sin 31\, t_r = -7.2\ \dot{\theta}_w$$

$$t_r = 0.032 \arcsin (-.043\ \dot{\theta}_w).$$

Since for small arguements arcsin x = x,

$$t_{r1} = 0.032\ (-.043\ \dot{\theta}_w)$$

$$t_{r2} = 0.032\ (\pi + .043\ \dot{\theta}_w)$$

$$t_{r3} = 0.032\ (2\pi - .043\ \dot{\theta}_w), \text{ etc.}$$

The net equivalent torque is the torque function integrated over one complete cycle; i.e.

$$T_{net}\ (\text{lb.-ft.}) = 4\ \frac{t1 - t2}{t1 + t2} = 4\ \frac{(t_{r2} - t_{r1}) - (t_{r3} - t_{r2})}{0.2} =$$

$0.113\ \dot{\theta}_w$, for $\dot{\theta}_w > 1$ radian/second and the total momentum coupled out of the gondola is $\int T_{net}\, dt = \frac{0.113\ \dot{\theta}_w}{p}$

In the limiting condition, with the reaction wheel at peak angular velocity (saturated), the momentum dump is capable of a constant 4 foot-pounds or alternatively of following a balloon angular velocity ($\dot{\theta}_{md}$) of 2π radians/minute.

ELEVATION CONTROL SYSTEM

The elevation system achieves its control by direct DC torquing at the elevation trunnion between the telescope and the gondola. The torquer is the same as that for the azimuth system and, like azimuth, the position and inertial mode control loops are completely independent except for the torquing function. A system block diagram is shown in Figure 9.

In position mode, the error voltage is derived from a linear, 5,000 ohm, 360° pot mounted on the elevation trunnion concentric with the elevation torque motor. The center tap of the pot is grounded, and with $\pm$ 5 volts across the winding; sensitivity is 1.60 volts/radian. Damping is achieved by feedback from a tachometer having a sensitivity of 1.20 volts/radian/second, also mounted on the elevation trunnion. The position loop is calculated to have a bandwidth of 0.4 radians/second and it is a type 1 loop (single kinematic integration) having zero position error.

Position commands are transmitted via the telemetry link as 12-bit words (LSB = 1.3 arcmin.) and converted to analog voltages by an on-board digital-to-analog converter. In order to minimize the effects of acceleration and jerk ($\frac{da}{dt}$) on the system which might excite high-frequency mechanical resonances or compound pendulum motion, the output of the DAC is operated on by a 0.03 radian/second rate limiter and a 2-pole 1.41 radian Butterworth low-pass filter before being fed to the error summing junction. A reduced block diagram of the elevation position loop is shown in Figure 10A.

In the inertial mode, the error voltage comes from a rate-integrating gyro identical to that used for azimuth. Here, however, the gyro senses elevation angle directly and no compensation of the sort used in azimuth is necessary. The gyro has a closed loop gain (including the gyro pickoff winding) of 35.3 volts/radian, and a nominal drift random rate of 3 arcmin./hour or less. Practically speaking, however, the drift is determined by the gyro control circuitry and is less than 1 degree/hour here and in azimuth (although anomolous higher rates have been observed in flight).

Error-rate damping is used in inertial mode, rather than output shaft velocity damping as in position mode. This choice was made to avoid the possibility of gondola disturbances appearing as velocity error inputs to the inertial loop. (Note that the telescope is intrinsically stable in elevation inertial position, independent of gondola motions except for bearing and cable loads.) A reduced block diagram of the elevation servo system in inertial mode is shown in Figure 10B. This is also a Type 1 system and has a calculated bandwidth of about 6 radians/second. A Bode plot showing the system response in the two modes is shown in Figure 11.

POINTING VERIFICATION

Intrinsic to any attitude controlled telescope is the problem of verifying its performance during actual flight. This is achieved by a variety of means. The elevation position is read out by two independent potentiometers through the telemetry; in azimuth readouts are provided of the azimuth position error (DAC output) and of an independent pair of cross magnetometers. For the inertial mode, readouts are provided of the gyro outputs indicating proper tracking. Overall pointing data are also provided in real time by a photometer, masked by a N-shaped aperture placed in the focal plane of the telescope, which senses the passage of stars down to 9th magnitude. Post flight data are provided by a star field camera mounted on the telescope which records the field of view frequently in automatic response to the various inertial mode pointing activities. These last two systems are discussed in more detail elsewhere (Fazio _et al_.,1974; Hazen, 1974).

BACKUP POSITIONING

Prompted by payload failures early in the flight program, an independent set of positioning drives has been incorporated into the gondola with enough readouts to be self-sufficient in the case of primary system failures. This backup capability uses the NCAR tone command system for control and is powered by an independent battery pack capable of several hours of continuous operation. The backup system is based on the concept of azimuth drift scanning at controlled elevation angles and is depicted in Figure 12, including a diagram of the command functions.

The elevation drive consists of a drive ring surrounding one elevation trunnion which upon activation engages a lug on the trunnion shaft. In practice, the operator uses a tone command (6) to enable the backup elevation drive, then uses two other tone commands (1 and 2) to drive the ring up or down, engaging the telescope and positioning it. Position accuracies to about 0.5 degrees can be achieved. Not shown in the figure is that the capture pawl is positively disengaged from the telescope when driven to elevation angles above 80°.

The backup elevation drive serves an additional purpose in providing means to stow the telescope in the vertical position prior to impact after a flight in cases where the primary systems fail or the payload is out of TM range. This is achieved by sending two tone commands (5 and 6) which initiate an automatic drive to the upper stop, or through a timer (set just prior to launch) and baroswitch (set to 30,000 ft.) which spontaneously initiate the same action during parachute descent. Both means serve also to switch off the main flight battery avoiding the problems of a powered payload during impact and recovery. Note also that this means can be used during flight to reset those DC-DC power supplies on the payload that a transient might trigger into crowbar cutoff. Easily cutting off and reinitiating total payload power is essential for resetting systems without going into a very elaborate alternative scheme.

Backup azimuth control is achieved by providing manual control of the momentum dump motor, using tone commands similar to those for elevation to permit torquing against the balloon. Although stationary positioning is difficult to achieve, azimuth rates can be kept sufficiently low to do effective drift scanning in the desired portion of the sky. One tone command (8) is used to clear the drive logic for both elevation and azimuth.

Note in Figure 12 that the primary flight battery is connected to the backup positioning system and, in fact, because of its higher voltage assumes the principal load except for the case of outright battery failure. There are also position readouts: a pot for the elevation and a pair of orthogonal magnetometers that monitor magnetic azimuth of the payload independently from the systems in the main section of the payload. For simplicity's sake, the active devices in the backup system are latching and momentary relays. Power and grounds run through separate paths from the power for the rest of the system.

COMMAND CONTROL

The command interface to which the payload was designed (ca. 1971) consisted of 20 sets of relay contacts, 10 sets momentary and 10 sets latched (thus involving 30 commands). Each momentary command provides a 25 ms connection of the common to the normally open contact. Otherwise, the common is connected to the normally closed contact. In the case of the latch commands, the common maintains its contact with one of the relay throws until the clear command is sent, when the common is brought into contact with the other throw. The relays are configured to provide TTL level outputs to the payload interface. Each normally open contact is connected to a +5V logic level through a 2.2K resistor. Each normally closed contact is connected to a signal ground. The common is brought to the interface as the command signal.

In addition, eight maintained switch closures were made available via a separate tone command system, where the duration of the switching is dependent on the duration of the tone. Here either ground or 24 volts are switched to the command input depending upon the application.

[Since the construction of the payload, NCAR has updated their commanding system (Snider, 1974). Funding limitations have forced us to retain the old input interface to the payload and to provide the adaption to the new by means of a relay interface box.]

Looking at the payload, a substantial number of functions have to be accommodated by command. The basic two axis positioning information requires 25 bits. In addition a large number of functions must be enabled and cancelled, and subsystems turned on and off. It was evident in the design that many of the commands would have to do multiple duty. A matrixing scheme was established, whereby 4 of the latching commands were used to address particular 13-bit registers and 7 of the momentary and the other 6 of the latching commands were used as signals into all of the registers. The remaining 3 momentary commands are used to control main power and to execute loads into the four registers. Figure 13 shows the scheme of the matrix. The first two registers are used to enter and store positional information for azimuth and elevation. The third register is used to "call" for certain payload functions, while the fourth controls the activation of major systems or functions.

In order to command the payload, the procedure is to address one of the four 13-bit registers, load the inputs to the register as required, execute (thus entering the load into the addressed register) and clear the address and the command load. The loads may, in general, be sent before or after the address, and the sequence of clearing after the execute is generally of no consequence.

To load an azimuth position, for example, the azimuth register is addressed (35), the desired azimuth position (13-bit word) is loaded, an execute is sent (32), then the addressing of the azimuth register is cleared (47) and the azimuth command bits are cleared. It is necessary to clear only the latching commands, since the momentaries are cleared at the last of the sequence that is initiated by the execute command (32). Figure 14 shows the logic to accomplish this and to otherwise achieve a high level of commanding reliability.

As a consequence of the momentary command load being cleared immediately after it has been loaded into its appropriate register, a lockout circuit was added to prevent a multiple execute command from entering a faulty command load. Thus, if more than one execute signal is received, the first one will perform the function and will block any others. Upon receipt of the command, the execute sequence enables and loads the addressed register, disables all registers to any inputs and clears the loaded momentary commands. In order to reenable the system to act upon an execute command, it is necessary to clear any outstanding register address. When faulty address codes are entered, the command system simply "enables" a non-existent register.

The third, or "call", register is handled a little differently. The desired function is addressed or "called"; then one of two "GO" tone commands is sent to actuate the function in the "plus" or "minus" direction. There are six functions of this sort (focus telescope, balance telescope, azimuth inertial scan, elevation inertial scan, momentum dump override and stow pin), and mutual exclusivity in these operations is advantageous in terms of noise immunity and simplicity of operation. A one-of-sixty-four decoder is therefore used at the output to monitor the status of those register outputs corresponding to the six desired functions. When one and only one of these six input lines is at a logic "1" state, the appropriate logic path is enabled and the "plus" or "minus" tone command will then actuate the function. When more than one function is "called", no system is actuated upon sending either of the GO commands.

Note that there are redundant pairs of GO commands. The tone commands provide immediate short term response (as for the focus drive); the matrix commands provide longer term enabling (as for an azimuth inertial scan). Logic not shown in the figure monitors the relevant outputs and precludes simultaneous use of more than one of these commands.

Unlike the first three registers, the register that turns systems on and off is used simply by addressing and loading, (not requiring execution). The momentary commands that appear as inputs to all of the registers are fed through this register, known as the 44 register, whenever it is addressed; these are used to turn on and off modes and systems by setting bistable devices.

The remainder of the 44 register (using latching commands) controls the power to the major systems in the payload, but since, as mentioned earlier, this register is entered by addressing and loading, it is easy to change its status. This possibility is minimized by means of "securing" the sub-register, whereby it must be separately enabled through one of two other registers in addition to its normal addressing. The functions controlled by the secure sub-register are normally turned on only once at the beginning of a flight for the duration.

Test and flight experience has shown this commanding scheme to be an effective means of controlling a payload of this complexity. Nonetheless, the new NCAR command equipment could provide significant simplification and will probably be utilized in future flights.

ACKNOWLEDGEMENTS

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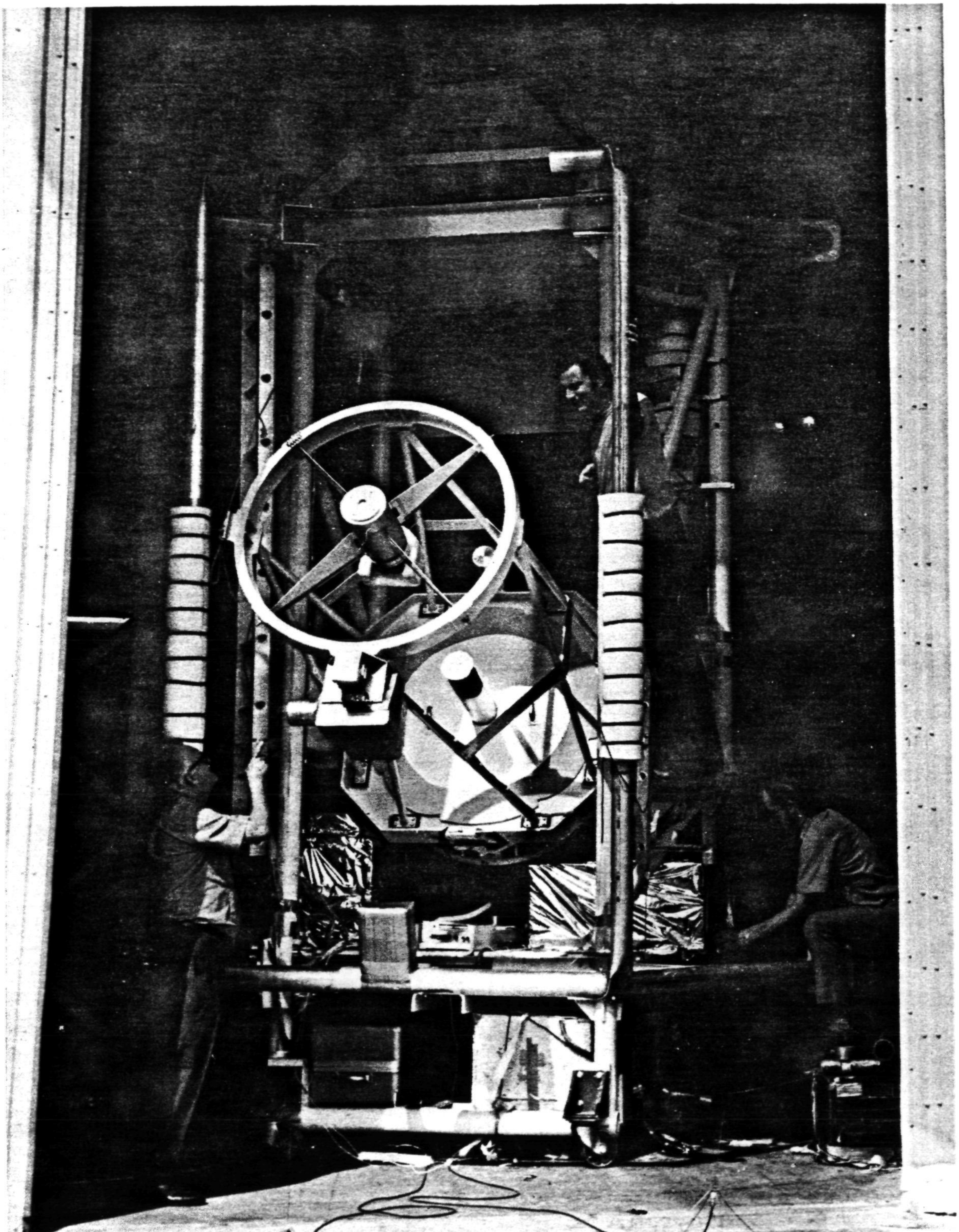

Figure 1. 1-meter IR telescope balloon gondola.

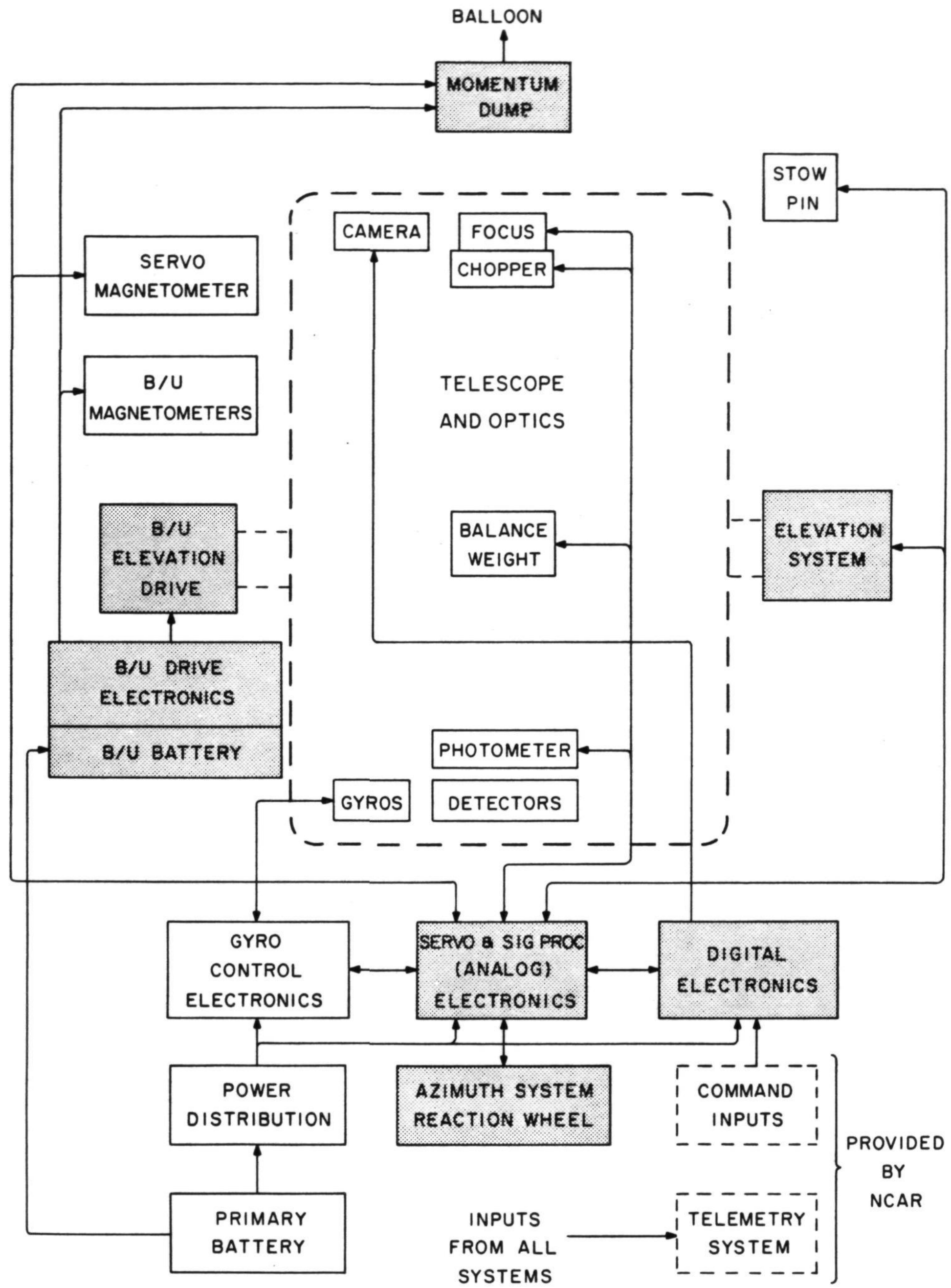

Figure 2. 1-meter telescope gondola - simplified block diagram.

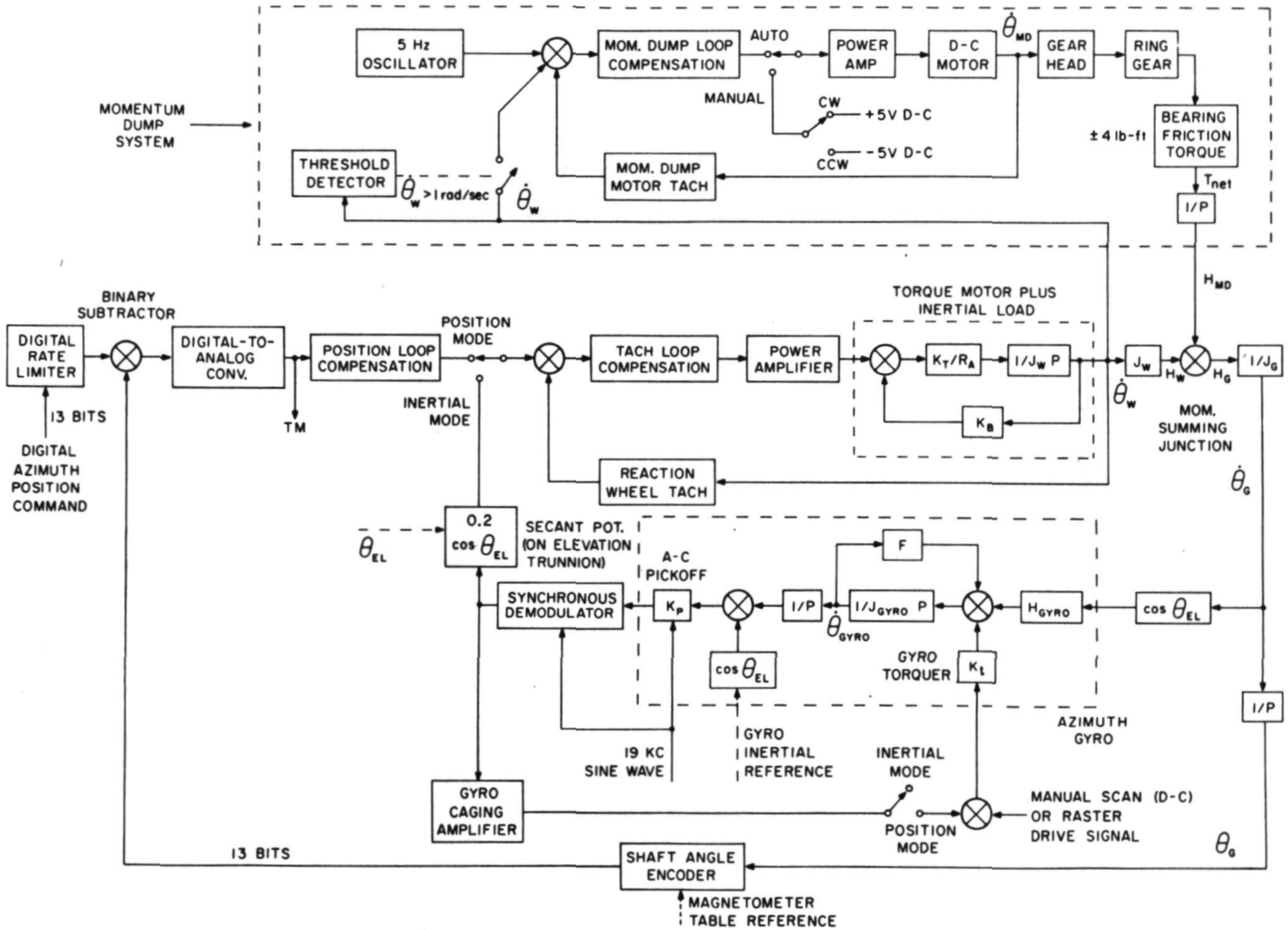

Figure 3. Azimuth control system block diagram.

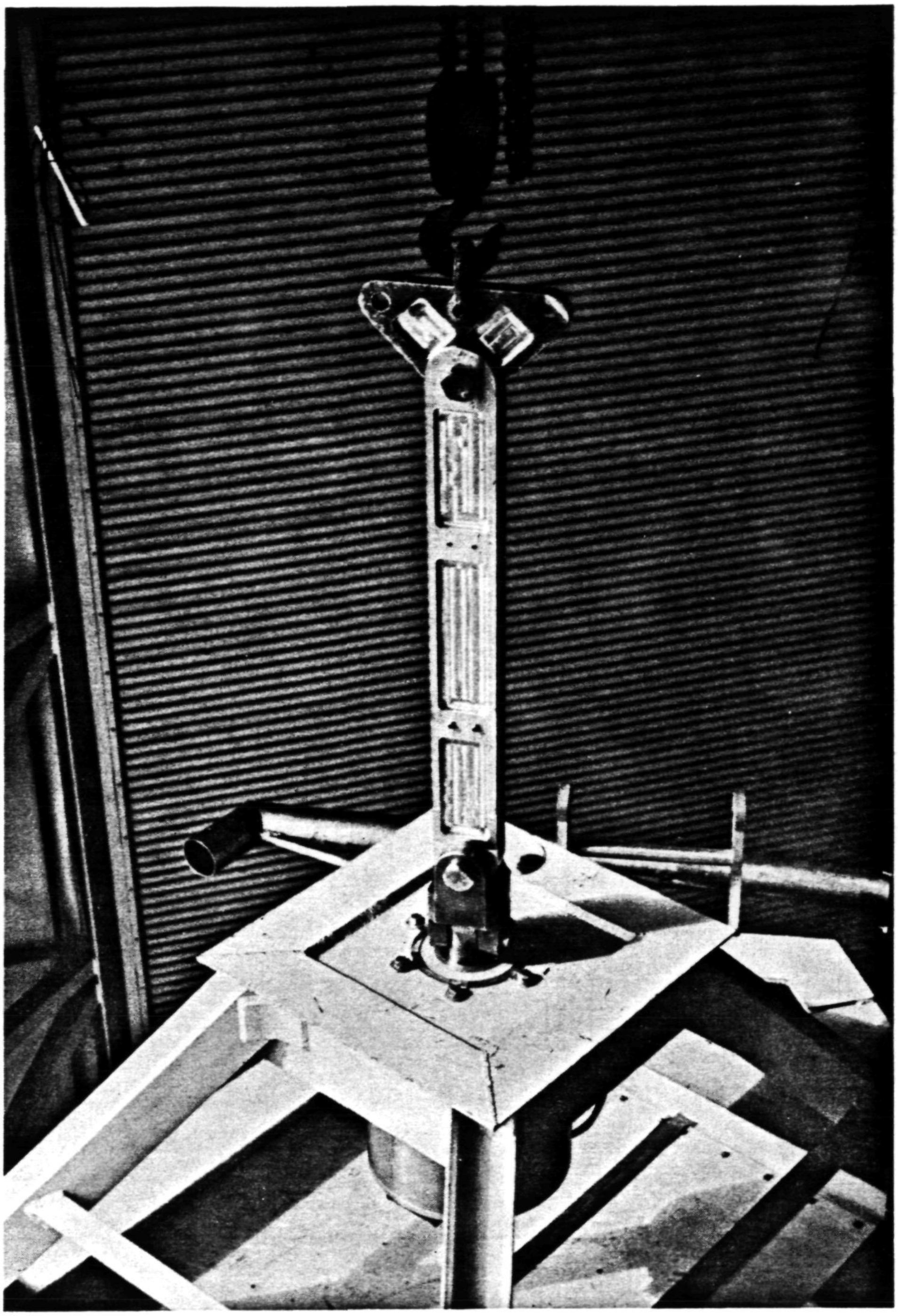

Figure 4. Suspension link (Inertia bar not shown).

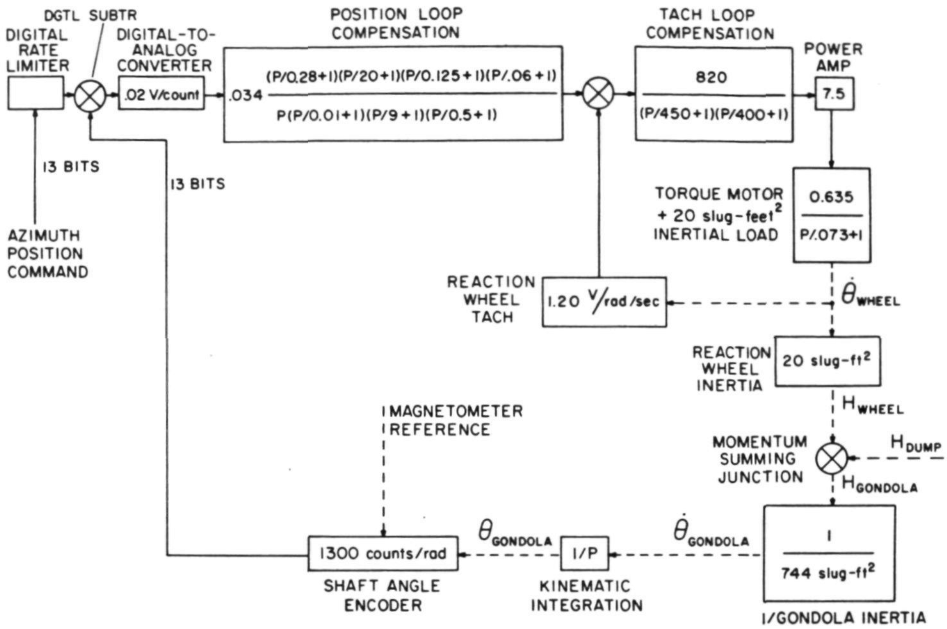

Figure 5A. Azimuth system reduced block diagram - position mode (momentum dump system not shown).

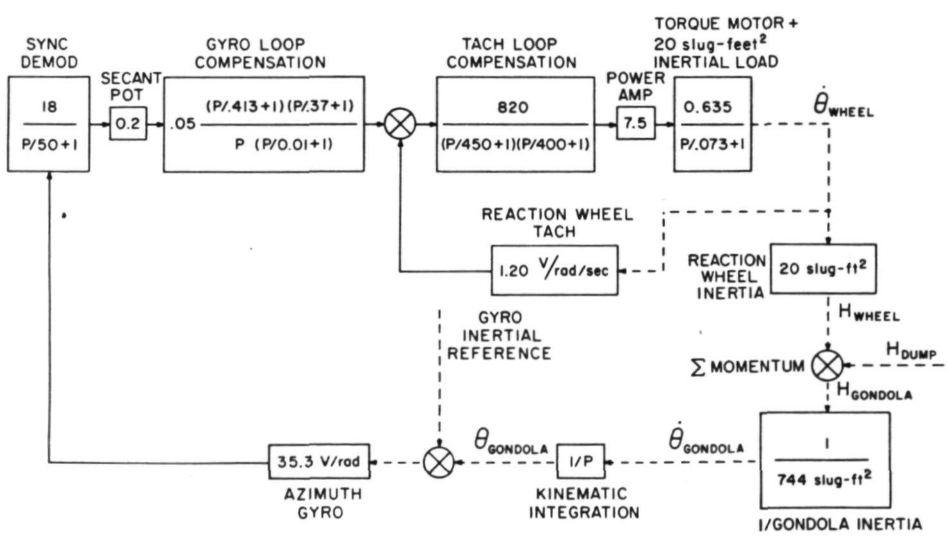

Figure 5B. Azimuth system reduced block diagram - inertial mode (momentum dump system not shown).

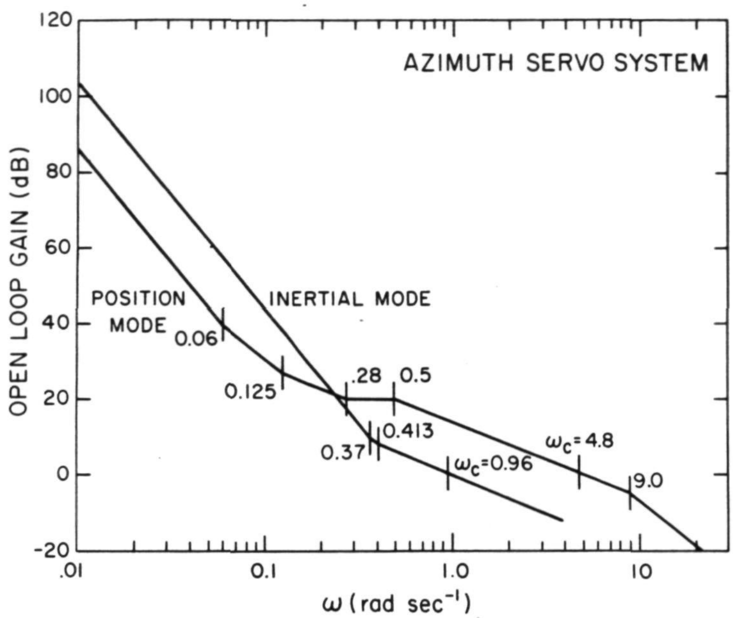

Figure 6. Azimuth servo system response.

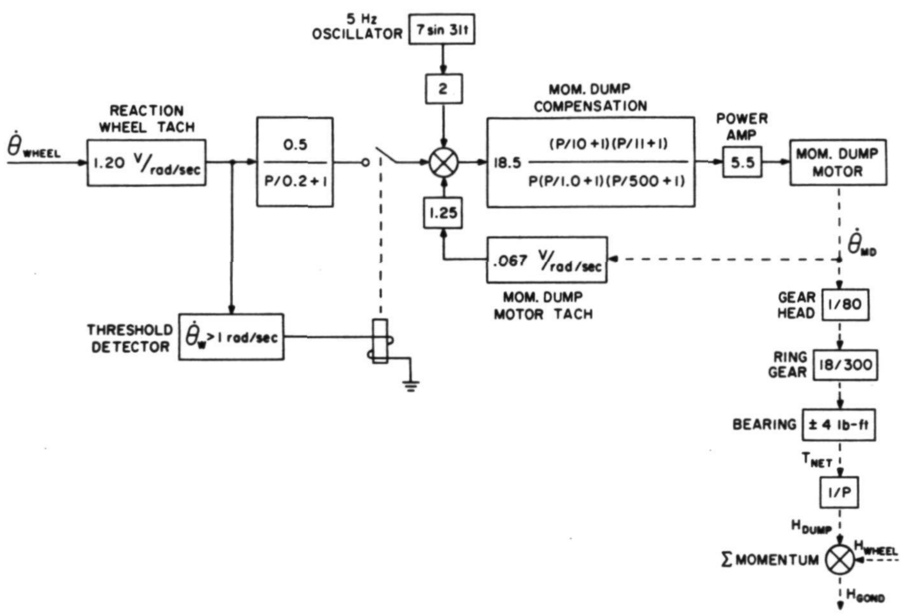

Figure 7. Momentum dump system - reduced block diagram.

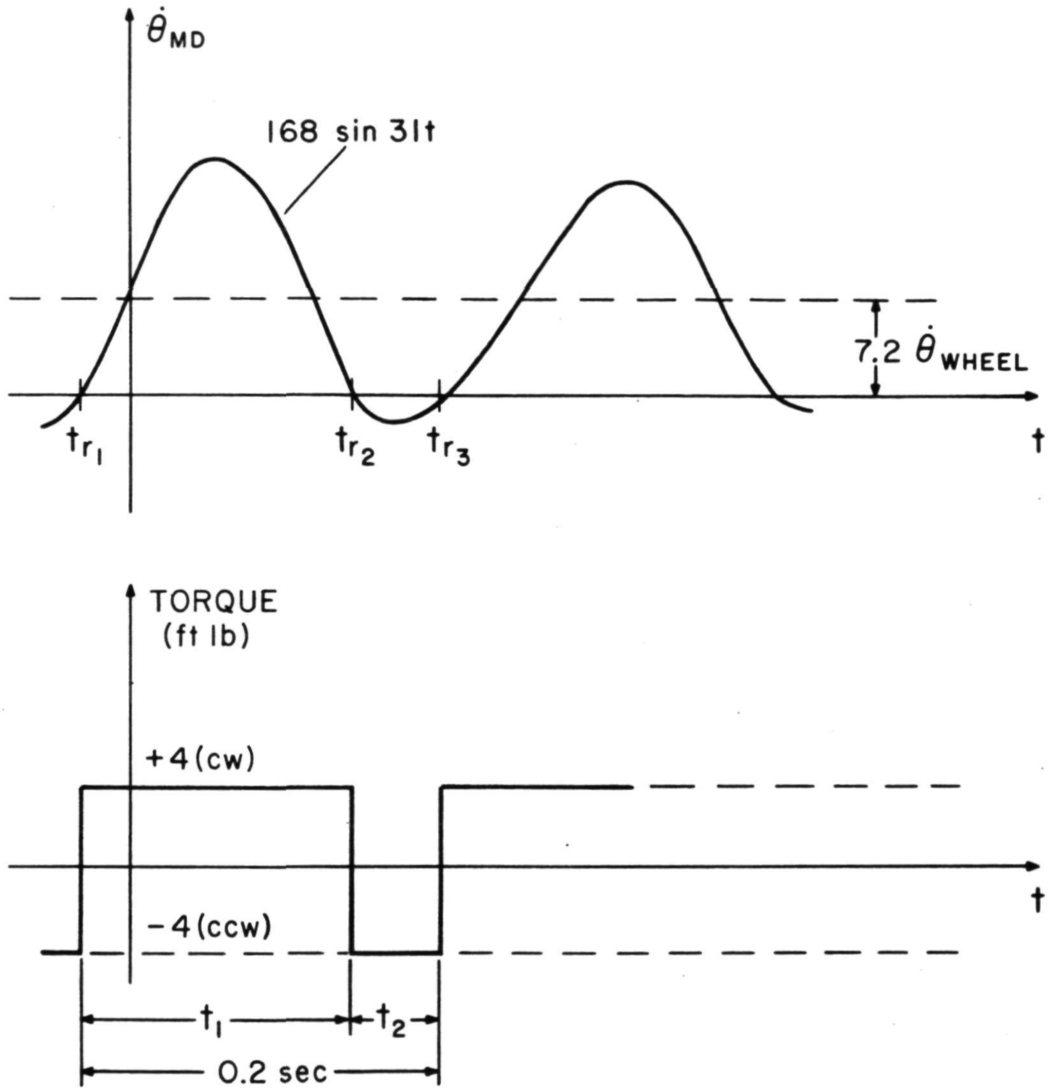

Figure 8. Momentum dump motor velocity and torque. Output vs. time.

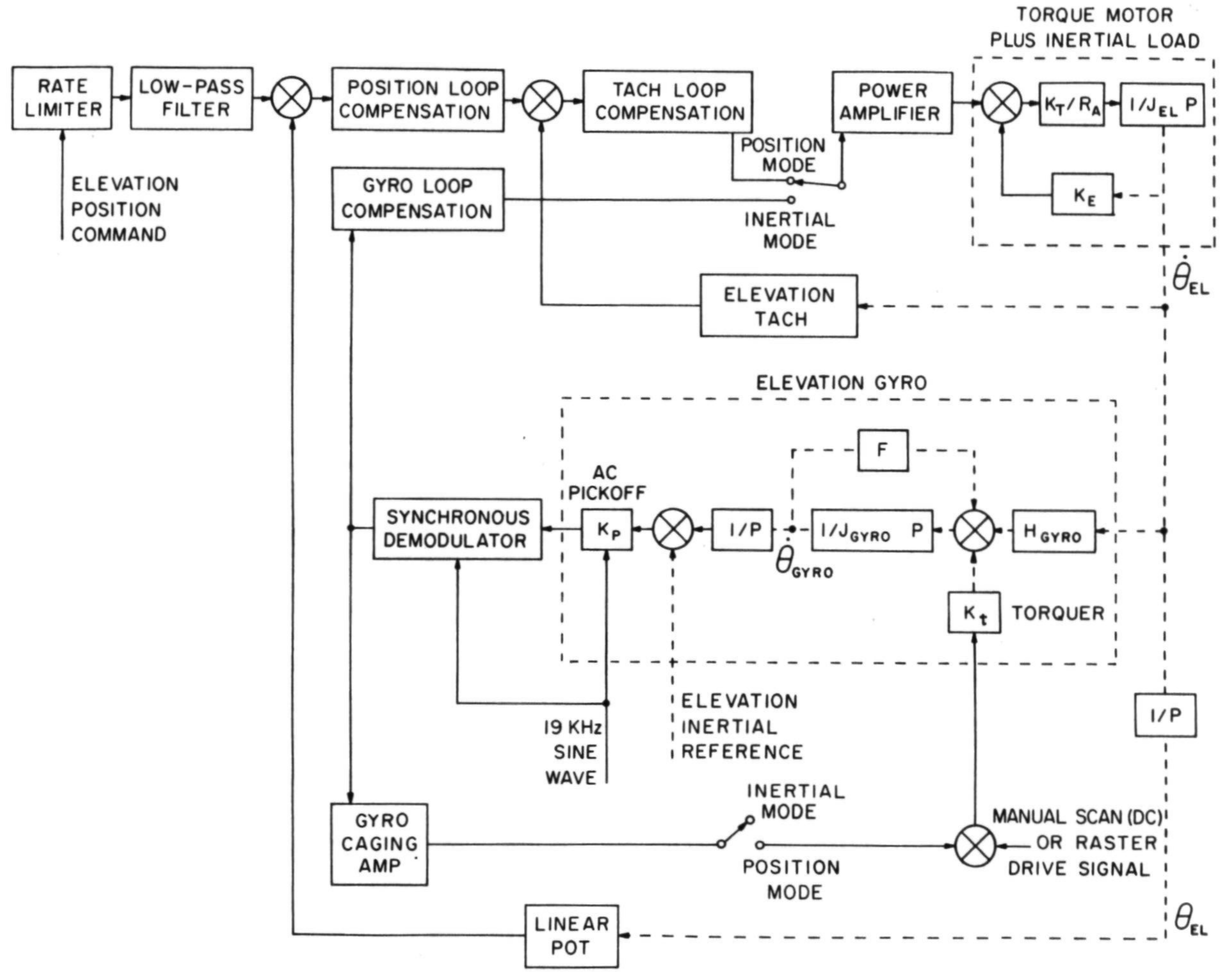

Figure 9. Elevation control system block diagram.

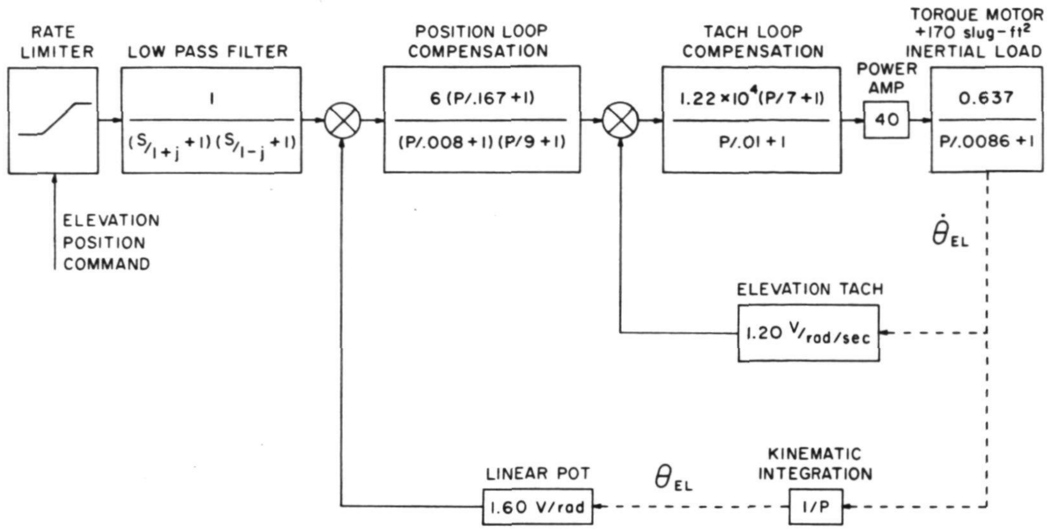

Figure 10A. Elevation system reduced block diagram - position mode.

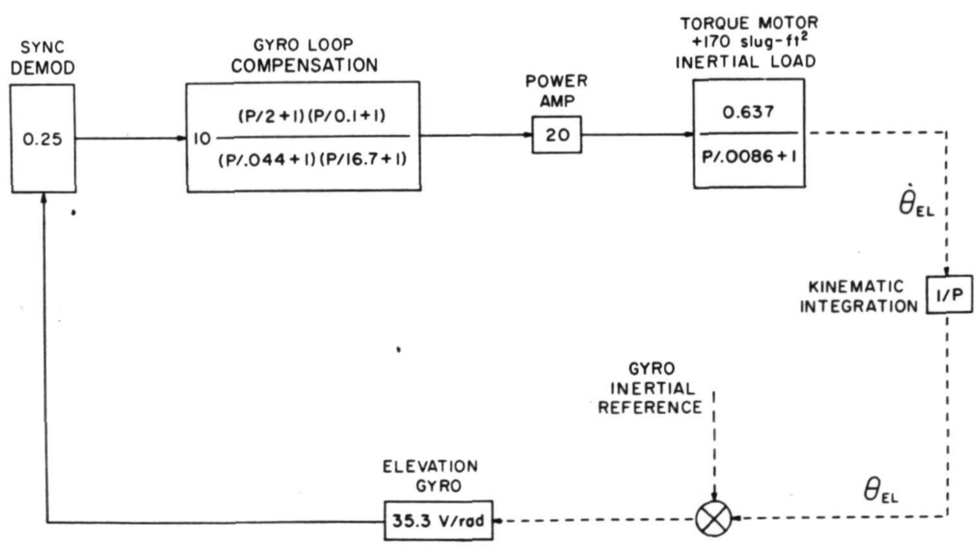

Figure 10B. Elevation system reduced block diagram - inertial mode.

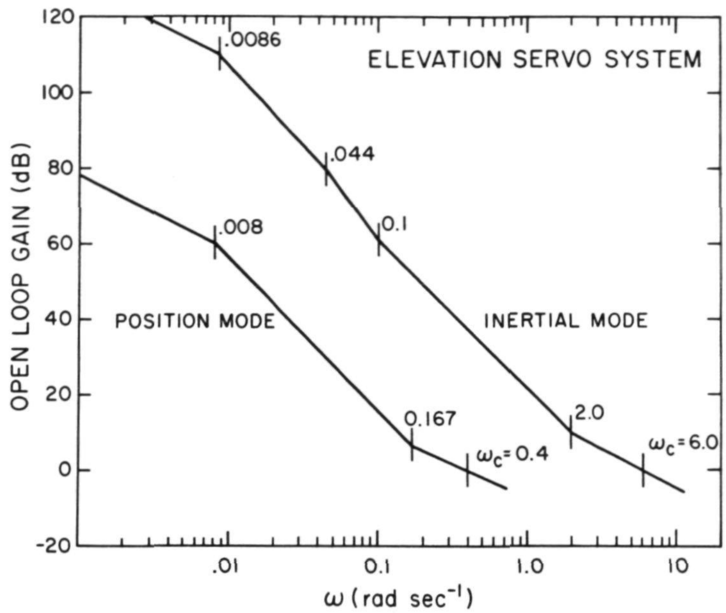

Figure 11. Elevation servo system response.

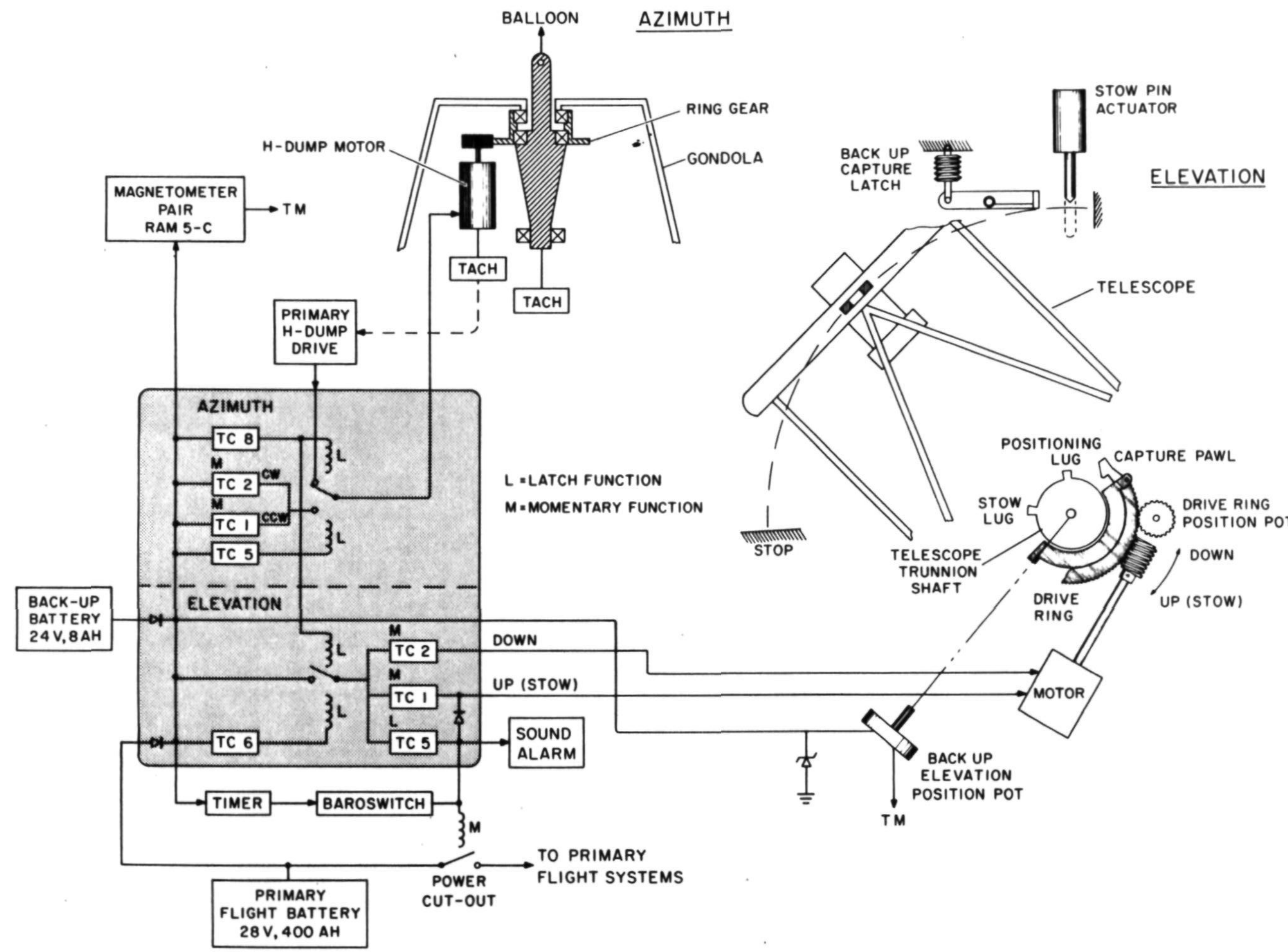

Figure 12. Backup drive and stow system block diagram.

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

Register		23	24	25	26	27	30	31	37	41	42	43	45	46	
REGISTER 35	AZIMUTH	.043°	.088°	.176°	.352°	.703°	1.405°	2.812°	5.625°	11.25°	22.5°	45°	90°	180°	UNLATCH 47
		—	—	—	—	—	—	—	51	53	54	55	57	60	
REGISTER 36	ELEVATION	CALL SECURE REGISTER	.022°	.043°	.088°	.176°	.352°	.703°	1.405°	2.812°	5.625°	11.25°	22.5°	45°	50
		—	—	—	—	—	—	—	51	53	54	55	57	60	
REGISTER 40		/	CALL FOCUS DRIVE	CALL BALANCE WEIGHT	CALL STOW PIN	CALL AZIMUTH INER.SCN	CALL ELEV. INER.SCN	CALL LARGE RASTER	CALL MANUAL H DUMP	GO +	GO -	/	/	CALL SECURE REGISTER	52
		—	—	—	—	—	—	—	51	53	54	55	57	60	
REGISTER 44		INERTIAL MODE ON	INERTIAL MODE OFF	GYRO WHEELS ON	GYRO WHEELS OFF	RASTER ON	RASTER OFF	/	/	AZIMUTH SYSTEM	ELEV. SYSTEM	H DUMP SYSTEM	N-SLIT SYSTEM	/	56
		—	—	—	—	—	—	—	51	53	54	55	57	60	

PLUS GO (+,-) COMMAND (Register 40, columns 24–37)

SECURE REGISTER (Register 44, columns 41–46)

NO REGISTER	32	33	34
	EXECUTE 35,36 40 LOAD	POWER ON	POWER OFF

	539	483	457	433	389	349	510	313
	1	2	3	4	5	6	7	8
	GO +	GO -	POWER ON BACKUP	TAKE A PICTURE	CALL AZIMUTH BACKUP	CALL ELEV. BACKUP	STOW PIN DOWN	CLEAR BACKUP

5 & 6 = AUTO STOW & BATTERY CUT OUT

Figure 13. Functional command matrix.

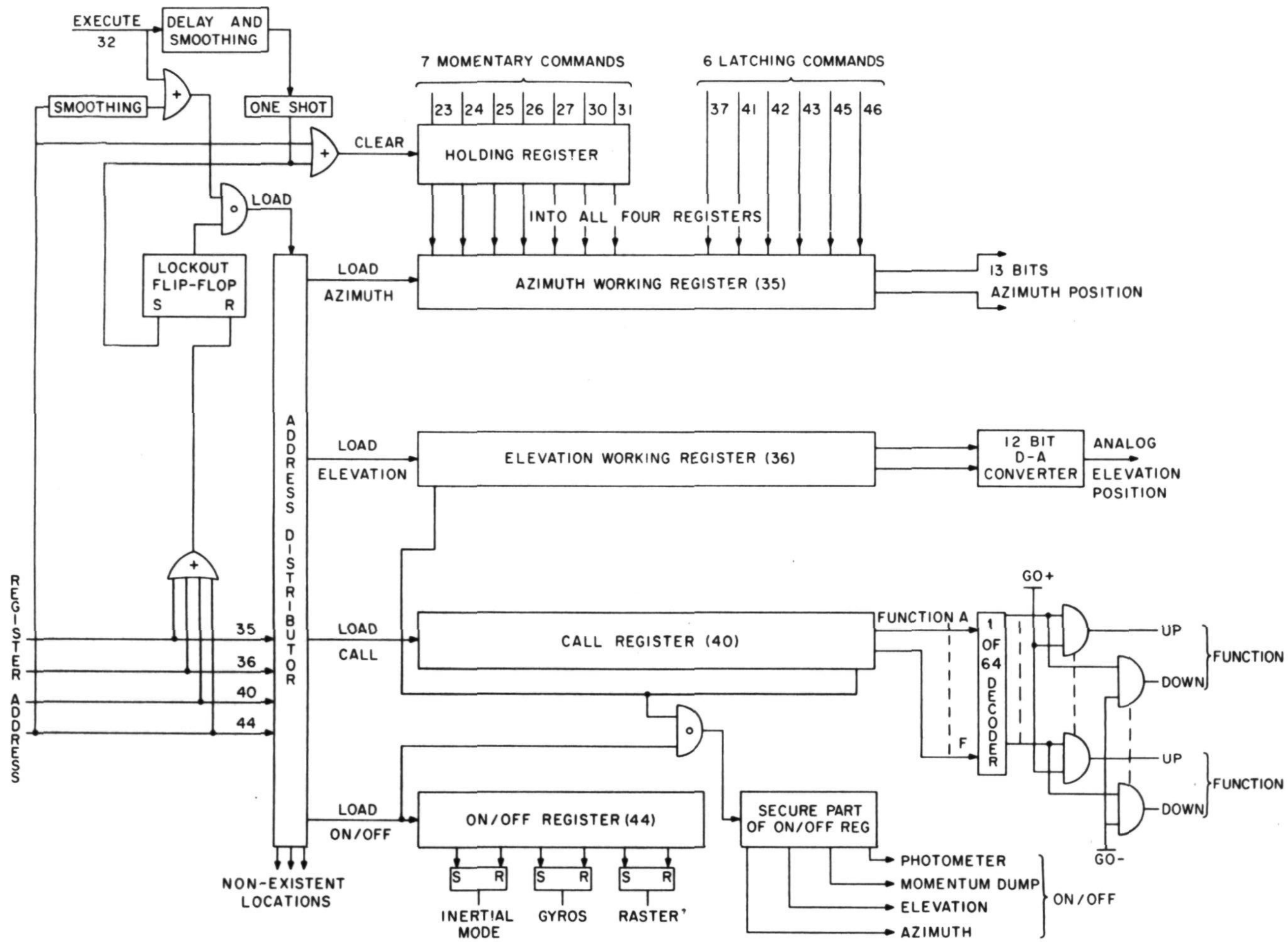

Figure 14. Command system block diagram.

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DISCUSSION SUMMARY — PAPER 4.4

Several questions were asked about details of the stabilization and pointing systems. These and the ensuing discussions are summarized below:

Q. How does the fact that the inertial wheel was not centered relative to the center of gravity of the payload affect the stabilization?

A. Torquing the reaction wheel causes a counterrotation of the payload around its center of mass. Furthermore, if that counterrotation includes a roll component, then the azimuth gyro will sense that and feed it back into the balloon. Consequently, the system becomes quasi-stable when pointed at high elevation angles. A quasi-stable small amplitude roll is built into the system with a frequency of about half a cycle per second, the component pendulum rate for this system.

Q. Why do you have a redundant system for pointing the telescope?

A. One or more of the primary systems failed in the first two flights, so redundancy was built in to ensure getting scientific data.

Q. Are the gyros good enough to do daylight observations?

A. The gyros are very good. They have drift rates on the order of 0.03° per hour, DC or random. The stability of the control circuitry is not that good and results in drift rates of about half a minute of arc per minute. This could be improved, but observations have not yet required it. Daylight observations have not been performed.

Q. Can you slew the telescope to view a non-visible object?

A. Yes. Inherent in the inertial loops is the ability to put in mission selectable scan rates by torquing the gyro and, therefore, causing the attitude control system to change.

Q. How good is the position mode (magnetic stabilization) in the presence of friction?

A. The friction isn't bothersome because the moment of inertia of the payload is such that an oscillating four foot pounds torque produces an oscillation at the five Hertz momentum dump rate of approximately 0.3 to 0.4 arcminutes. Pointing performance has been consistently better than a tenth of a degree in stability (not absolute) for times on the order of five or ten minutes.

Q. How much friction do you have in the main bearing?

A. The system was designed to withstand up to 10 g's without damage. The payload weighs 400 pounds, so the bearing is rated at 40,000 pounds. It has two joint tapered roller bearings. Under dynamic conditions their torque (running torque) was measured at four foot pounds. They are oscillated in order to control this. The break-away torque has not been measured but is felt to be significantly higher.