CR 73291

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THE IMPACT OF BIOSCIENCES REQUIREMENTS ON BIOSATELLITE ATTITUDE CONTROL

Canaveral Council of Technical Societies
Space Congress
Cocoa Beach, Florida

Pages - 24
Code - 1
CR - 73291

N69-21661

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The design, development, and flight test results of the Biosatellite attitude control system shall be discussed. Preliminary remarks describing the several Biosatellite missions shall show how mission constraints were interpreted by the controls engineer and how the "zero - g" and recovery requirements were ultimately translated into attitude control performance criteria. Results of analyses of payload perturbing effects shall answer questions of the nature: What are the forces and moments to which the payload is sensitive? From what sources are these disturbances derived? How can payload accelerations of the order of 10^{-5} - g be sensed and controlled in a practical and economic way?

The paper shall also include a discussion on the prominent role a continuing simulation activity played in the development of the attitude control system. Of particular interest to the controls oriented engineer will be the discussion stressing the importance of these simulation studies to the analysis and evaluation of control system performance in the deorbit phase of the mission. Here, performance of state-of-the-art hardware will be evaluated and its selection justified. Also included in these remarks will be comments on the effects of geophysical phenomena on sensors and how these were incorporated in the simulation program to enhance its validity. Control system configuration shall be defined and features, such as the versatility of recovery time and location, will be discussed.

The Biosatellite Mission

The Biosatellite Program is another stepping stone to man's deeper understanding of the biological world. His curiosity and zeal have led to the development of a highly technological society which today finds itself on the brink of a biological explosion. The significance of the role to be played by Biosatellite in this era is still to be determined. However, an indication of what is being sought is contained in the opening remarks by Dr. D.W. Jenkins, Assistant Director, Biosciences Programs, NASA Headquarters at the symposium on the Biosatellite II experiments. In it he states:

> "The space environment presents an opportunity to biologists to study the basic properties and nature of living Earth organisms with new tools previously unavailable and opens up new areas of research for which biological theory fails to provide adequate predictions. The components of the space environment of importance to biologists are weightlessness, weightlessness combined with

> radiation, the absence of the Earth's 24-hour periodicity, and cosmic radiation with energies and particle sizes unmatched by anything produced artificially on Earth."[1]

The Biosatellite Program was established to provide the biologist the orbiting laboratory he required to achieve these otherwise unachievable set of conditions. Orbital conditions for this program call for a nominal inclination of 33.5° and altitudes ranging from 170 to 200 nautical miles depending on mission duration.

As evolved, Biosatellite is a multimission program consisting of two three day Radiation and General Biology Missions and two Primate Missions lasting up to thirty days. The purpose of the three day mission (which has been completed) was to determine: (A) the effects of weightlessness at the cellular, organ, and organism level, and on the physiologic and behavioral responses of the organism; (B) the biological effects of radiation in combination with weightlessness. The purpose of the primate mission will be to determine the prolonged effects of weightlessness on a higher form of life.

Mission Requirements

With the emphasis on weightlessness clearly established, a more precise definition of what was required by the experimenter was needed to determine what it would take to provide such capability. The requirement thus established, stressed that a degree of weightlessness of less than 1/100,000-g for 95% of the time in orbit be maintained.

Another requirement defined as essential by the experimenter was that payload recovery must be achieved to obtain the scientific results on all experiments.[2] It was upon these basic constraints that a rather intricate automatic system has been developed to provide the near zero gravity environment and to assist in the recovery of the experiment payload. This system is the Biosatellite attitude control subsystem (ACS).

Attitude Control Studies

Translation of the above requirements into a definite system configuration was not a readily obvious procedure; particularly, in the mechanization of the controls to assure the degree of weightlessness specified. Early consideration of the problem indicated that the approach to follow should be one in which the sensing as well as the control of payload accelerations would be accomplished economically and reliably. The most attractive solution proposed and later implemented was to provide the spacecraft with the capability of rate damping. With this approach, it was possible to employ rate gyros as the primary sensors and to rely on a simple pneumatic system to provide control torque. However, before such a scheme could be accepted, it was necessary to show by analysis that mission requirements would not be sacrificed. This activity led to the development of an analogue computer simulation program to permit solution of the equations of motion. In the rudimentary stage, the simulation results provided only limited information insofar as payload accelerations were concerned, but were quite adequate in defining control gas requirements for the mission and verifying the adequacy of active rate control once per orbit. The next stage in the evolution of the Biosatellite simulation was its expansion into a hybrid setup. This increased capability permitted continuous calculation of total acceleration levels at any desired point in the capsule. More on the hybrid simulation will be discussed later.

As already stated, sensing and controlling to near zero gravity was found to be within the capability of a rate damping system. It was found that the acceleration due to body motion of any point in the payload capsule could be expressed by the following equation:

$$A_i = [A_{xi}^2 + A_{yi}^2 + A_{zi}^2]^{1/2} \tag{1}$$

where i defines the point in the capsule

$$A_x = -R_x(\omega_y^2 + \omega_z^2) + R_y(\omega_x\omega_y - \dot{\omega}_z) + R_z(\omega_x\omega_z + \dot{\omega}_y) \tag{1.1}$$

$$A_y = -R_y(\omega_z^2 + \omega_x^2) + R_z(\omega_y\omega_z - \dot{\omega}_x) + R_x(\omega_x\omega_y + \dot{\omega}_z) \tag{1.2}$$

$$A_z = -R_z(\omega_x^2 + \omega_y^2) + R_x(\omega_x\omega_z - \dot{\omega}_y) + R_y(\omega_y\omega_z + \dot{\omega}_x) \tag{1.3}$$

Early analysis showed that vehicle rates below 0.286 deg/sec were required to satisfy the 1×10^{-5} - g limit, and a torque to inertia characteristic of 0.045 deg/sec^2 was necessary to prevent exceeding the 1×10^{-4} - g limit. Figures 1 and 2 show the ACS in the rate control mode and define rate switching limits, respectively.

During these early studies, it was realized that the spacecraft would be subjected to disturbances that could effect payload acceleration. Sources of such disturbances were investigated and evaluated to determine their magnitudes. It was found that aerodynamic drag would also be significant and as a first approximation a value of 0.5×10^{-5} - g was established. This effect was combined with the body rate accelerations and provided a degree of conservatism to subsequent analyses and established a minimum orbital altitude of 140 nautical miles to maintain the 1×10^{-5} - g requirement. With the advent of the hybrid simulation effort, more precise studies showed that the minimum altitude could be reduced to 115 n. m.[3]

Disturbance Torques

As a free body, the motion of the orbiting Biosatellite spacecraft is affected by external and internal torques and angular momentum changes. Torques included in the externally applied category are:

Aerodynamic
Gravity Gradient
Magnetic
Solar Radiation

Those torques considered as internally applied include:

Gas and Fluid Transmission and Dumping
Rate Gyro
Recorder and Other Motor Driven Devices
Primate Activity

Results of detailed analysis of each source of disturbance clearly established the major torque contributors as aerodynamic, gravity gradient, and fluid dumping.

Predominant among these is the fluid dumping effect which is exclusive to the Primate Mission. This torque is generated everytime the water boiler exhausts overboard (Figure 3). However, the alignment of this port is critical and is tightly controlled by specification. It is required that final adjustment be made after the spacecraft center of gravity is determined in the field. This procedure is necessary to assure that the maximum impulse developed does not exceed 15-inch pound seconds per orbit. Since boiler operation is not a programmed function, the ACS to be used in the Primate flight will have the added capability of automatic rate control; a feature not used in the three day flights. The control system, in the automatic rate control mode, now has the ability to sense high rates, turn itself on, and turn itself off. For the 3-day flight a ground command was required to activate the rate control function.

Insofar as the aerodynamic and gravity gradient torques are concerned, their values are dependent upon spacecraft attitude and the maximum values calculated are 3.4×10^{-3} ft. lb. and 2.7×10^{-4} ft. lb., respectively.[4] These torques are 90° out of phase so that their maximum values cannot occur simultaneously. Flight test results of both three day missions show that these effects on vehicle motion were well within anticipated levels and that the once per orbit rate control philosophy to limit power consumption was well founded.

Unfortunately, results of both three day flights showed that initial outgassing after orbit injection was greatly underestimated. In this instance, the problem was found to be caused by a thin mylar overlay covering the foam insulation surrounding the payload capsule.

This overlay was sufficiently air tight to greatly retard depressurization of the foam during powered flight. As a result, high rates were developed between ground station contacts during the first day of both flights.

Aerodynamic Drag

Aerodynamic drag is an important consideration in determining the orbital lifetime of a near earth satellite. Mission analysis studies have determined that the nominal injection altitude for the thirty day primate flight is 200 nautical miles, while the nominal 3 day target altitude was 170 n.m. After injection, orbital altitude will decay because of aerodynamic drag, whose effect is to reduce the speed of the space-craft. Hence, the payload will also feel the effect of this braking action. Calculation of the total acceleration experienced by the experiments must, therefore, include drag effects. This was accomplished by defining total payload acceleration in the following manner:[5]

$$\bar{a} = \frac{\bar{D}}{W} + \frac{\bar{A}}{g} \qquad (2)$$

where

$\bar{a}$ is total acceleration vector in g's

$\bar{D}$ is drag force in lbs.

W is spacecraft weight in lbs.

$\bar{A}$ is payload acceleration due to body motion ft/sec^2

The drag force (D) can be expressed as:

$$D = Cd \ \frac{1}{2} \rho \, V^2 \ A_{ref}$$

where

Cd is the aerodynamic drag coefficient

ρ is the atmospheric density in slugs/ft^3

V is the orbital velocity in ft/sec

A_{ref} is the reference area in ft^2

Atmospheric data (Figures 4 and 5), show that density varies by an order of magnitude in the nominal altitude range for the Primate Mission. A corresponding change in drag acceleration would be experienced by the space-craft as its orbital altitude decays. As shown in Figure 5, the maximum acceleration at a minimum altitude of 130 nautical miles would be less than $.5 \times 10^{-5}$ g.[6] Consequently, when this factor is taken into consider-ation, higher rates can be tolerated at higher altitudes as shown by the results of simulation studies plotted in Figure 6.

Control Torques

In order to comply with acceleration requirements, careful consideration was given to the selection of the control torque level to be used. As seen by examination of equations 1.1 to 1.3, the angular acceleration is used directly in these equations while only the centrifugal effects of angular rates contribute to the payload acceleration. Thus, when applying rates and acceleration values designed into the system, it is seen that the control torque ($0.045^\circ/\text{sec}^2$) effects are 2 to 3 orders of magnitude greater than those contributed by the centrifugal effects where the rates are limited to $0.286^\circ/\text{sec}$.

The philosophy followed here was that since the disturbance torques were very small, the time required to build up spacecraft rates to the threshold value would be quite long. Consequently, actuation of the control thrusters would be infrequent and would not develop an accumulated time greater than 5% of the orbital period (4.5 minutes). The decision was made to provide the maximum allowable control torque without violating the maximum 1×10^{-4} - g limit. Figure 7 shows the results of the analysis performed to establish this level. Point A, indicated on the graph is illustrative of the control system's ability to maintain the low gravity required. Interestingly enough, the 1×10^{-4} - g limit is maintained even during the deorbit phase of the mission when the ACS is called upon to orient and stabilize the spacecraft for retro-fire.

Simulation Program

Before proceeding with ACS deorbit mode performance, it might be well to digress slightly at this point to describe the simulation program developed in support of subsystem design and evaluation activity. Early plans that touched on simulation studies were directed at generating substantiating data for sizing cold gas storage requirements and further verifying the adequacy of the subsystem control concept. These goals were easily met with a conventional analog setup. However, as the demand for more data, and the need for design trade-off information mounted, the digital computer was added to expand the capability of the simulation effort. Aside from calculating accelerations mentioned previously, it was also now possible to accurately simulate digital logic functions of the attitude control programmer (ACP), include spherical harmonic model of the Earth's magnetic field via the expediency of punched cards, locate the spacecraft over any point on Earth, and provide sun and cloud geometry conditions. Every facet of the simulation program was exercised during the very active period between the first and second flights. In addition to evaluating the effects of proposed design changes for the Biosatellite II spacecraft, some simulation work was also performed to verify later primate mission capability which featured automatic rate control. The hybrid simulation also proved invaluable in explaining a problem encountered during the flight of Biosatellite I. A block diagram of the complete Biosatellite simulation is shown in Figure 8.[4] Vital to deorbit mode operation is the position information provided by two IR scanners and the control logic contained in the attitude control programmer. Breadboard models of the IR sensors and control logic were built and actually tied into the simulation to determine the effects of sun and clouds on ACS performance.

Deorbit Mode Operation

It is the function of the deorbit mode to position the spacecraft in the prescribed deorbit attitude so that, after retro rocket burnout, the re-entry capsule will follow a predetermined trajectory to the recovery point. Figure 9 shows the vehicle in the proper deorbit attitude. This figure also shows the three position sensors used; they include two IR scanners for pitch and roll, and a magnetometer for yaw. The block diagram (Figure 10) shows where in the system rate gyro and position sensor data are combined to provide the desired control logic. Switching lines defined in Figure 11 show the exact rate and position conditions under which attitude control solenoid valves would be energized to control spacecraft motion.

IR Sensors

Because the spacecraft is allowed to tumble randomly during the orbital phase of the mission, special control logic based on IR sensor output has been designed into the system to provide the capability for acquiring the deorbit attitude from any orientation. The following paragraphs shall elaborate on this logic function and describe its impact on the Biosatellite I flight. But first, it is necessary to have a clear understanding of how the IR sensor output is used. IR sensor pulse data is processed in the ACP which makes the decision as to whether there is a valid earth presence signal. Earth presence is determined on the basis of how much of the Earth the scanner sees as it rotates at a frequency of 30 cps (see Figure 12). Specific threshold values are necessary to establish this bit of logic. It is required that the magnitude of the earth pulse be greater than 1.2 volts and its duration must be between 18 and 80% of a nominal duty cycle. If earth presence is not established when the deorbit mode is initiated, then a roll search function is generated which actuates the negative roll solenoid and causes the spacecraft to start rolling. This maneuver will eventually cause one or both scanners to acquire the Earth. Once earth presence is established, roll search is terminated and scanner position data is processed causing the vehicle to stabilize in pitch and roll. After this has been achieved, and body rates are below 0.280°/sec., yaw switch is then closed thus introducing the magnetometer signal into the yaw loop.

Having thus defined the purpose of earth presence logic in the sequence of deorbit attitude acquisition, some additional explanation of how it is determined is warranted at this time, particularly, since earth presence continues to play a control function after the spacecraft is essentially stabilized. Because the IR scanners are vulnerable to sun and cloud effects which induce errors up to 10°, the system logic was originally designed to inhibit roll and pitch position error inputs whenever these effects were encountered. The means used for making this determination was earth presence. Basically, the logic used was if an invalid pulse were detected, the earth presence signal would be removed (see Figure 13). With position data inhibited, the vehicle would be allowed to drift until the disturbance disappeared. However, flight test results from Biosatellite I showed that this philosophy worked to the detriment of the ACS. The problem experienced involved a thermal blanket which was taped down around the scanner aperture at assembly. It is conjectured that the tape came loose during powered flight or while in orbit and partially obscured the scanner field of view as seen in Figure 14. This condition gave rise to what has since been described as the "Daylight Effect." This effect was so called because everytime the satellite emerged into sunlight, earth presence was lost in the pitch channel and ultimately caused complete loss of attitude. Once the spacecraft entered darkness, deorbit attitude was reacquired and maintained. The problem was diagnosed as the result of heating of the thermal blanket by the Earth's albedo which caused an invalid pulse and loss of earth presence. In Biosatellite II, the problem was rectified by changing the blanket configuration and the logic. Earth presence as now designed required only that a valid pulse be detected. Any additional pulses, regardless of source, will not effect the state of the earth presence logic. Flight test data from Biosatellite II verified that "Daylight Effects" were no longer a problem.^{7} It is to be noted that despite the daylight problem of Biosatellite I, spacecraft attitude at the deorbit point was satisfactory due to the planned early morning recovery which required a night-time deorbit.

Sun and Cloud Effects

Since sun and cloud effects are still potential error sources, use of sun geometry computer programs and advanced weather data is made in selecting the deorbit, or call down, location. The concern for clouds stems from the response of the IR sensor to the contrast in apparent temperatures. The sensor is particularly susceptible to clouds on either the leading or trailing edge of the earth pulse. A cloud in the middle of the pulse, provided it is not too cold, will not create an error. A typical scanner signature when the sun is encountered, was obtained during the Biosatellite II flight. The sequence of IR sensor pulses in Figure 15 show how a sun pulse near the horizon increases in magnitude as the spacecraft yaw position changes.

Magnetometer

The role of the magnetometer is to provide yaw control after the conditions of earth presence, roll and pitch position, and three axis rates are satisfied. Of particular interest to this discussion is that yaw attitude is a function of location in orbit, or more precisely, a function of the local magnetic field. Response to magnetic field conditions at points other than the specified deorbit location gives rise to wide excursions in spacecraft yaw attitude with respect to the orbital plane which can vary as much as 90°. In order to assure accurate yaw alignment at deorbit and to provide flexibility in the selection of this point, the magnetometer has been equipped with a separate bias circuit which is controlled by ground command. It is possible to apply a zero to ± 250 milligauss bias to the magnetometer. Analyses of magnetic field data and flight results indicate the adequacy of the bias values provided. Mechanical alignment of the magnetometer probe with respect to the spacecraft is also given consideration when planning a mission so that the bias can be kept reasonably small. There is a twofold reason for exercising such caution. The first reason is the tendency of a sizeable bias field to increase the yaw loop dead band which, in effect, reduces accuracy. The second effect is, in essence, the limit of the first where the bias field either equals or exceeds the nominal horizontal Earth's field at a particular point in the orbit. In such a situation there is a temporary loss of reference because it is impossible to obtain a suitable magnetometer null. Fortunately, only one such point has been encountered and it is located in the vicinity of South Africa.

ACS Tests

Testing of the ACS was, and is, performed in several phases. The first full scale subsystem test was the three axis air bearing test which permitted checkout of every aspect of subsystem operation. The purpose of these tests was to verify subsystem design and performance criteria and predict orbital operation. Figure 16 is a picture of the air bearing table.[8] Essential elements of the ACS mounted on it are appropriately designated. A schematic representation of the air bearing facility is shown in Figure 17.

The air bearing facility offered a unique opportunity of testing and evaluating subsystem performance under almost ideal conditions. Use of the air bearing allowed nearly frictionless motion so that control gas usage was not excessive. The simulated earth inside the water cooled "teepee" provided a good IR model for checking scanner performance and evaluating earth presence logic. Finally, results of these tests were analyzed and minor design changes recommended and implemented. Subsequent subsystem tests included ACS checkout after installation into the adapter; electrical mate tests - where the entire spacecraft is electrically hooked up; mechanical mate tests - where the spacecraft is assembled in its flight configuration; and a series of environmental tests where the vehicle is exposed to vibration and thermal vacuum conditions. Each flight vehicle is subjected to a complete cycle of acceptance and confidence tests prior to shipment to Kennedy Space Center. All data generated is closely monitored to assure proper performance in flight.

Conclusion

The Biosatellite attitude control subsystem has successfully demonstrated its capability for providing the zero gravity environment during Flights I and II. One significant change introduced to cope with unpredictable disturbance torques anticipated for the forthcoming Primate Mission is the automatic rate control feature. With this capability, it will be possible to also control vehicle rates should outgassing be in evidence as it was previously. Deorbit mode capability has not been changed save for the combining of roll and pitch earth presence logic to further mitigate its effect after initial stabilization is achieved.

References

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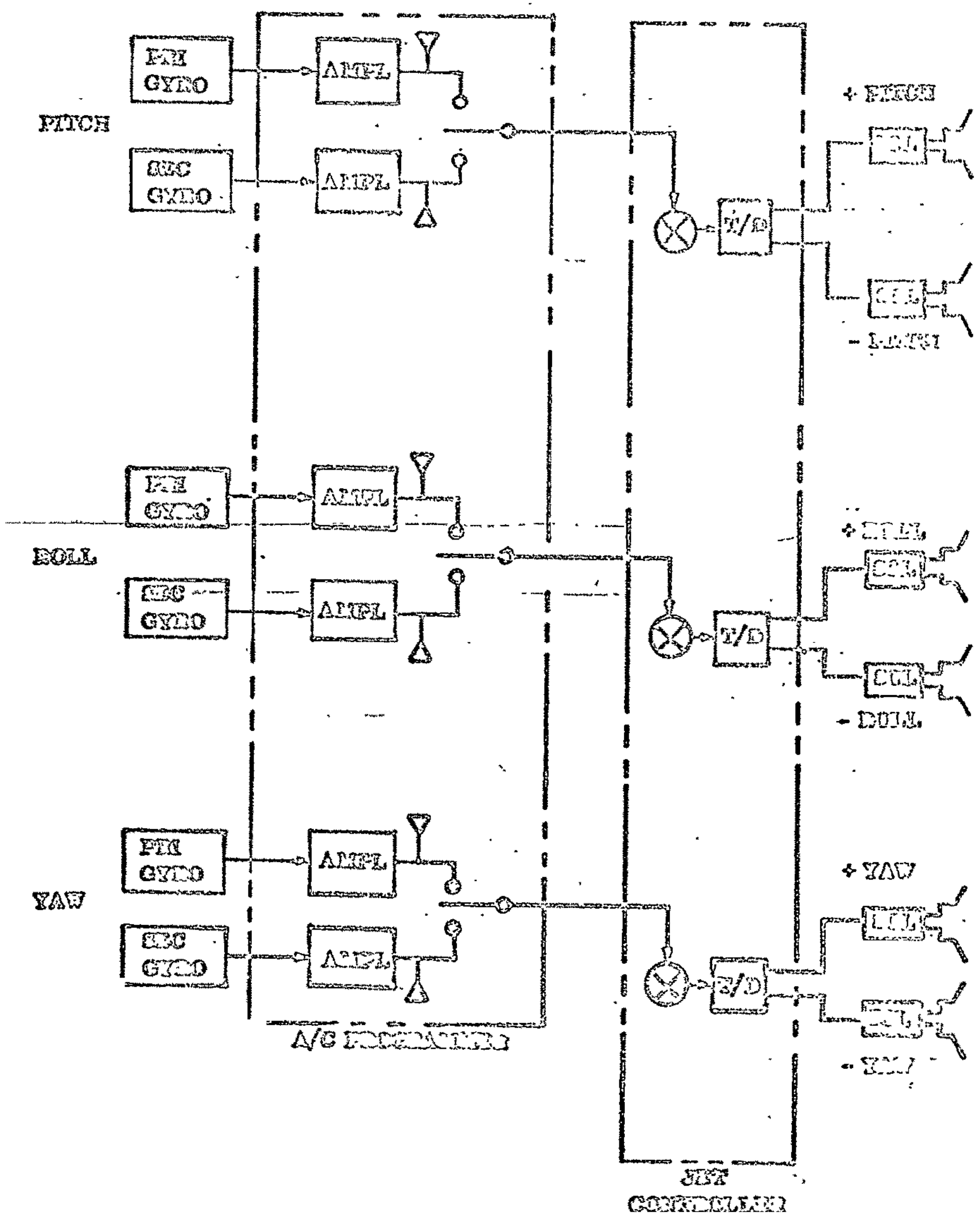
This paper is based on NASA CR 73291 prepared for Ames Research Center under contract NAS2-1900.

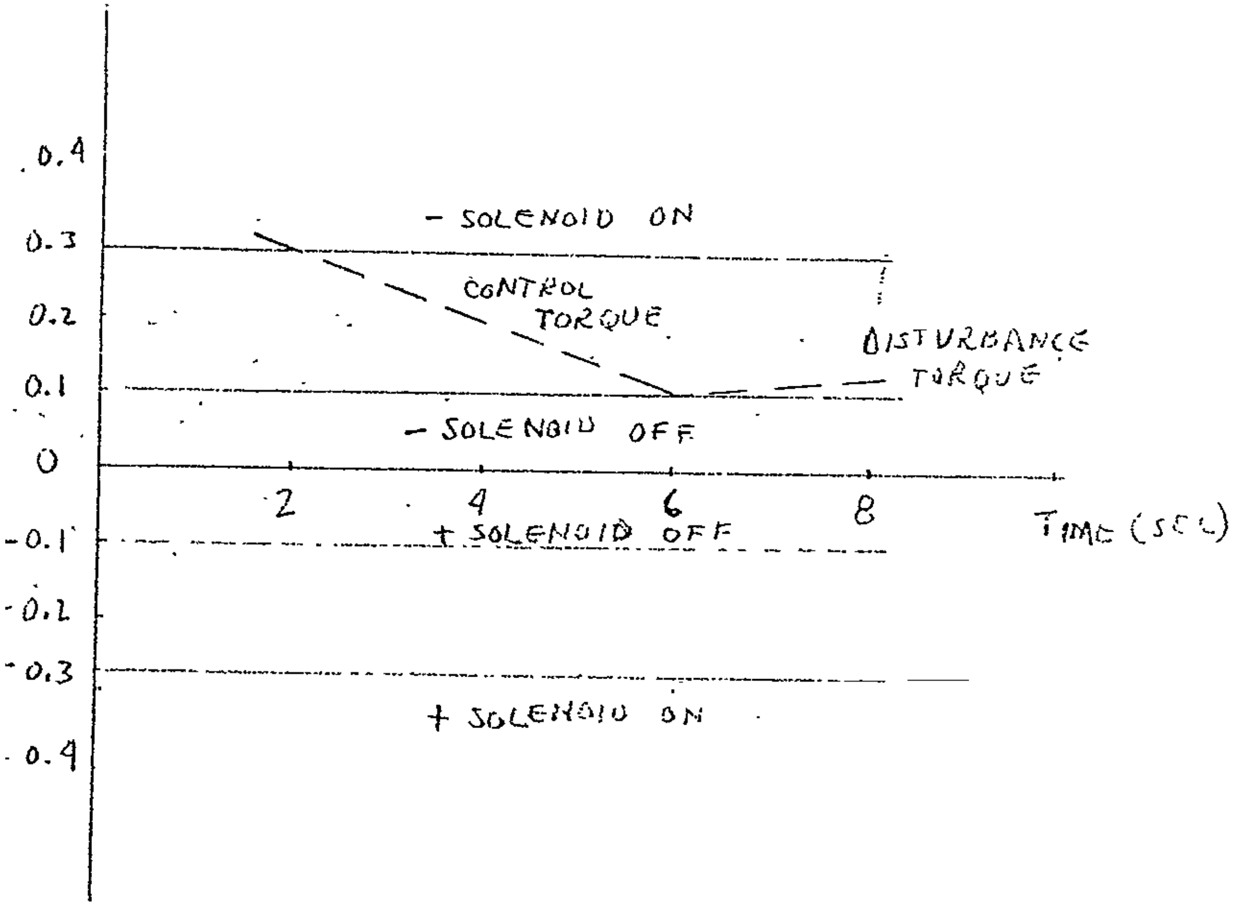
ACS RATE CONTROL MODE

FIGURE NO. [illegible]



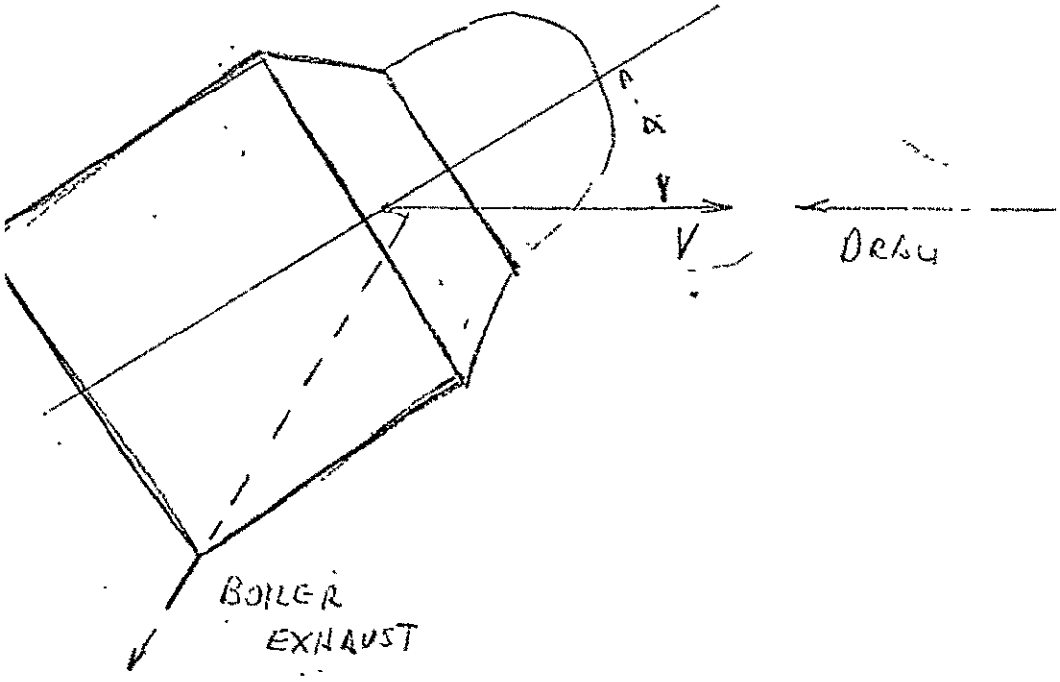
RATE CONTROL SWITCHING LINES

FIGURE NO. 2



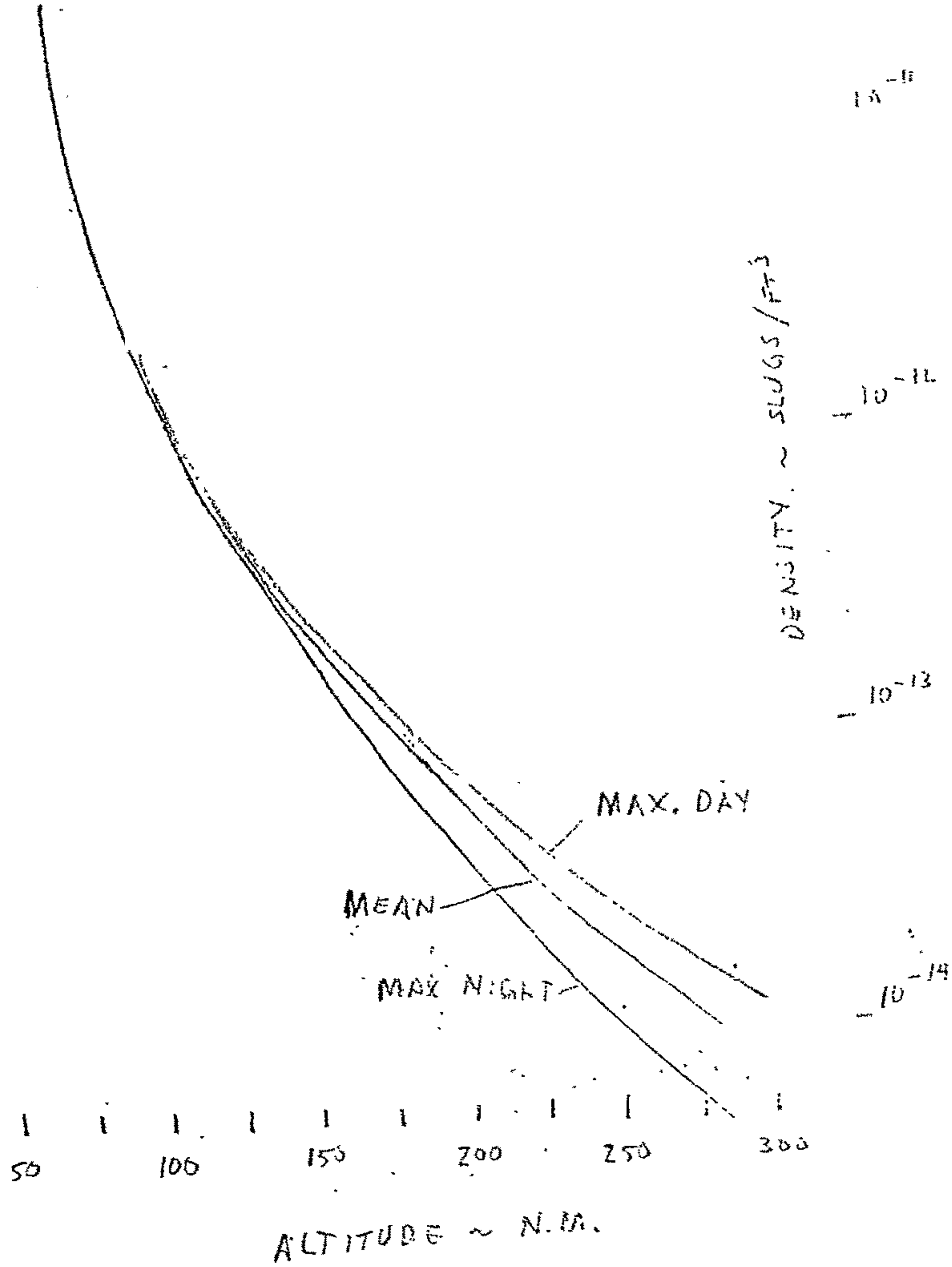
BIOSATELLITE SPACECRAFT IN ORBIT

FIGURE NO. 3



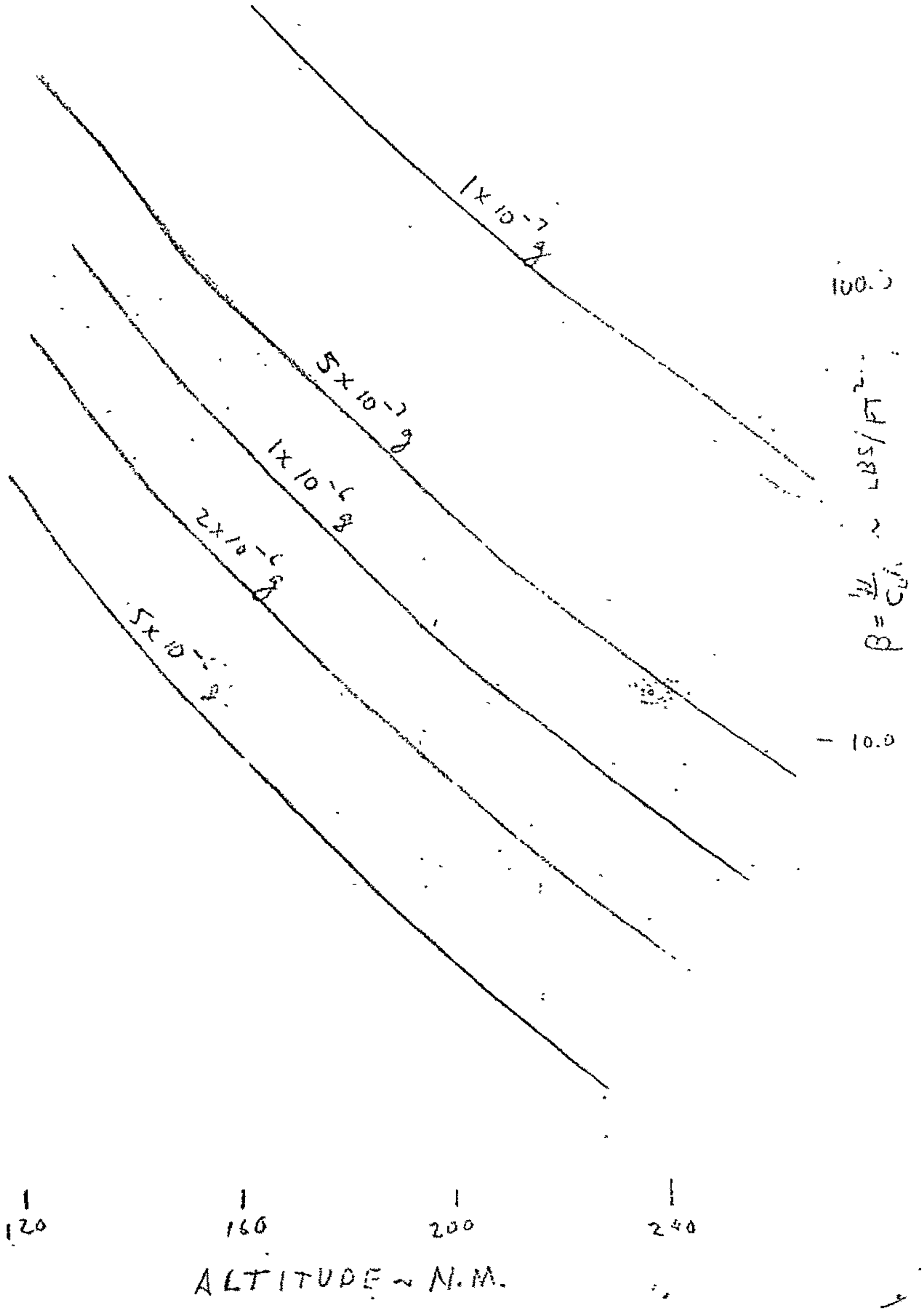
DENSITY VS. ALTITUDE

FIGURE NO. 4



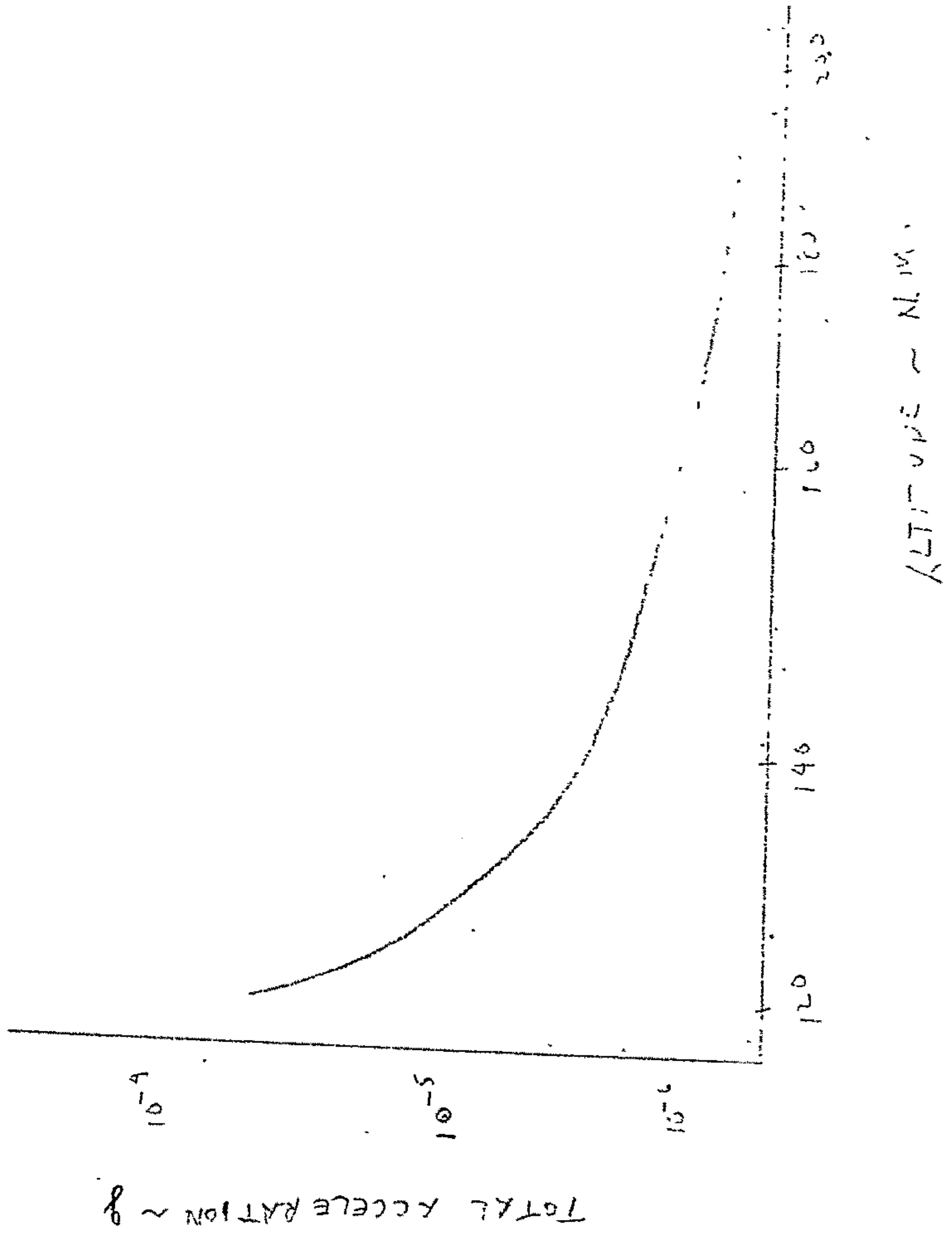
DRAG ACCELERATION VS. ALTITUDE

FIGURE NO. 5



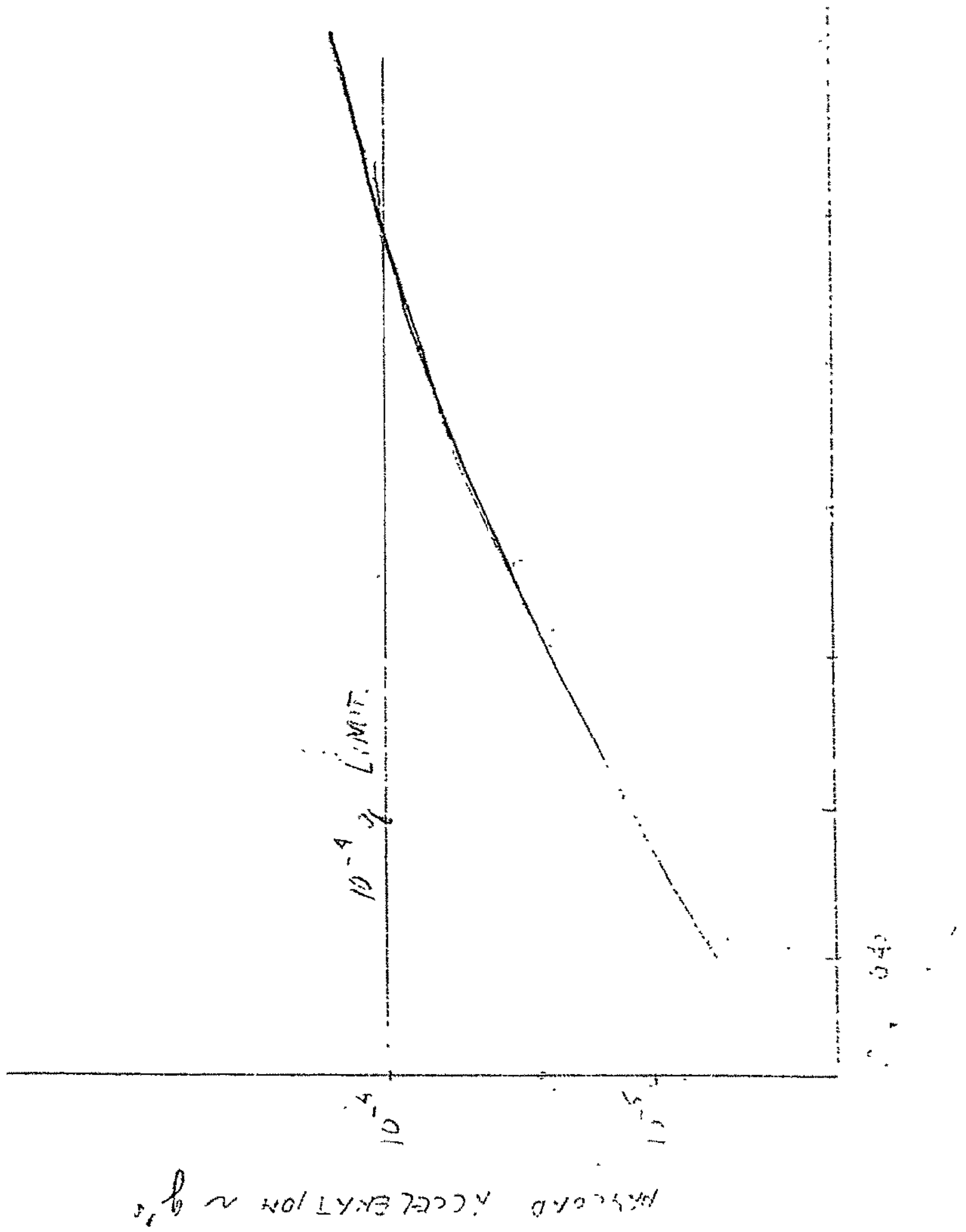
TOTAL ACCELERATION VS. ALTITUDE

FIGURE NO. 6



CONTROL TORQUE SELECTION

FIGURE NO. 7



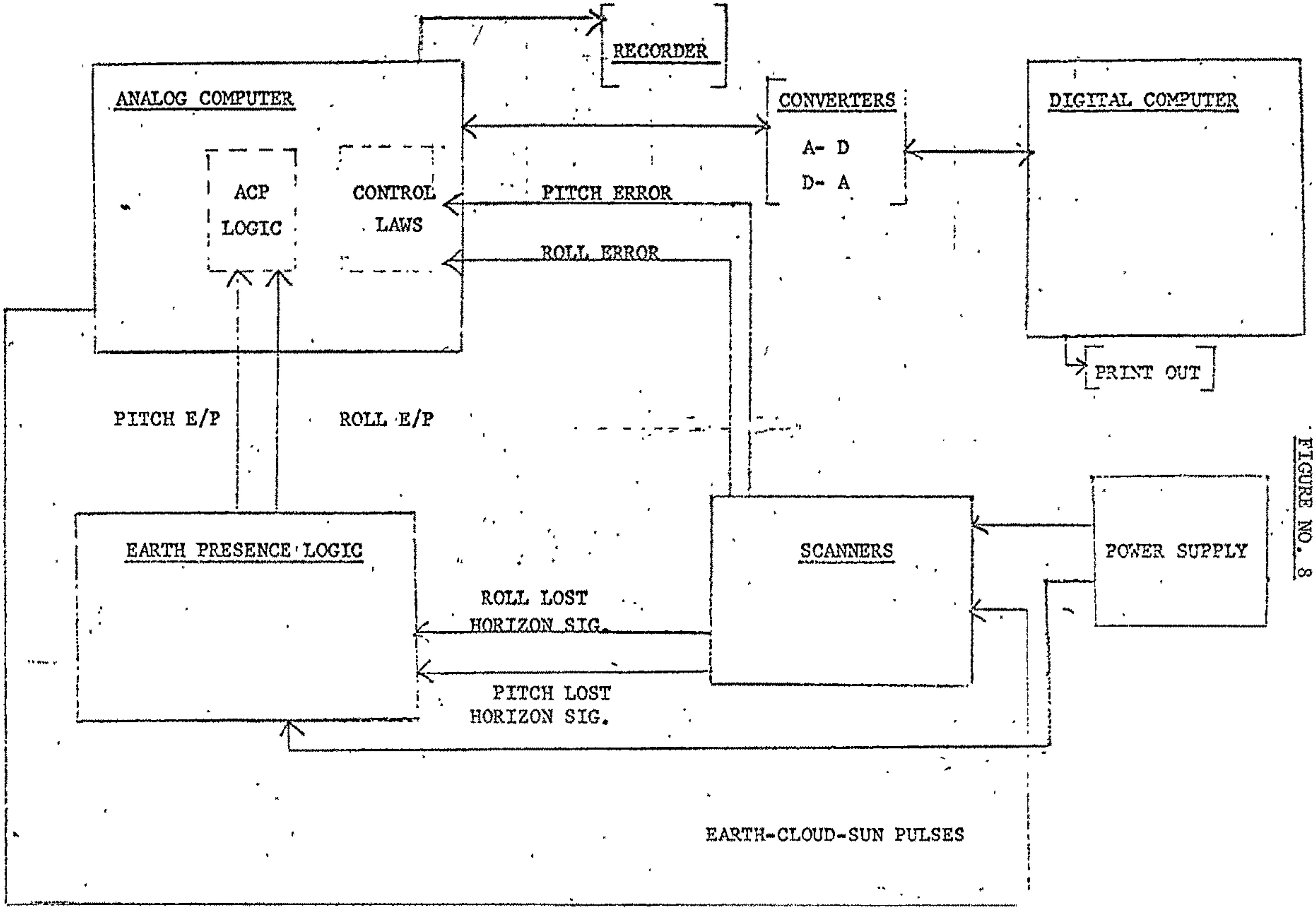
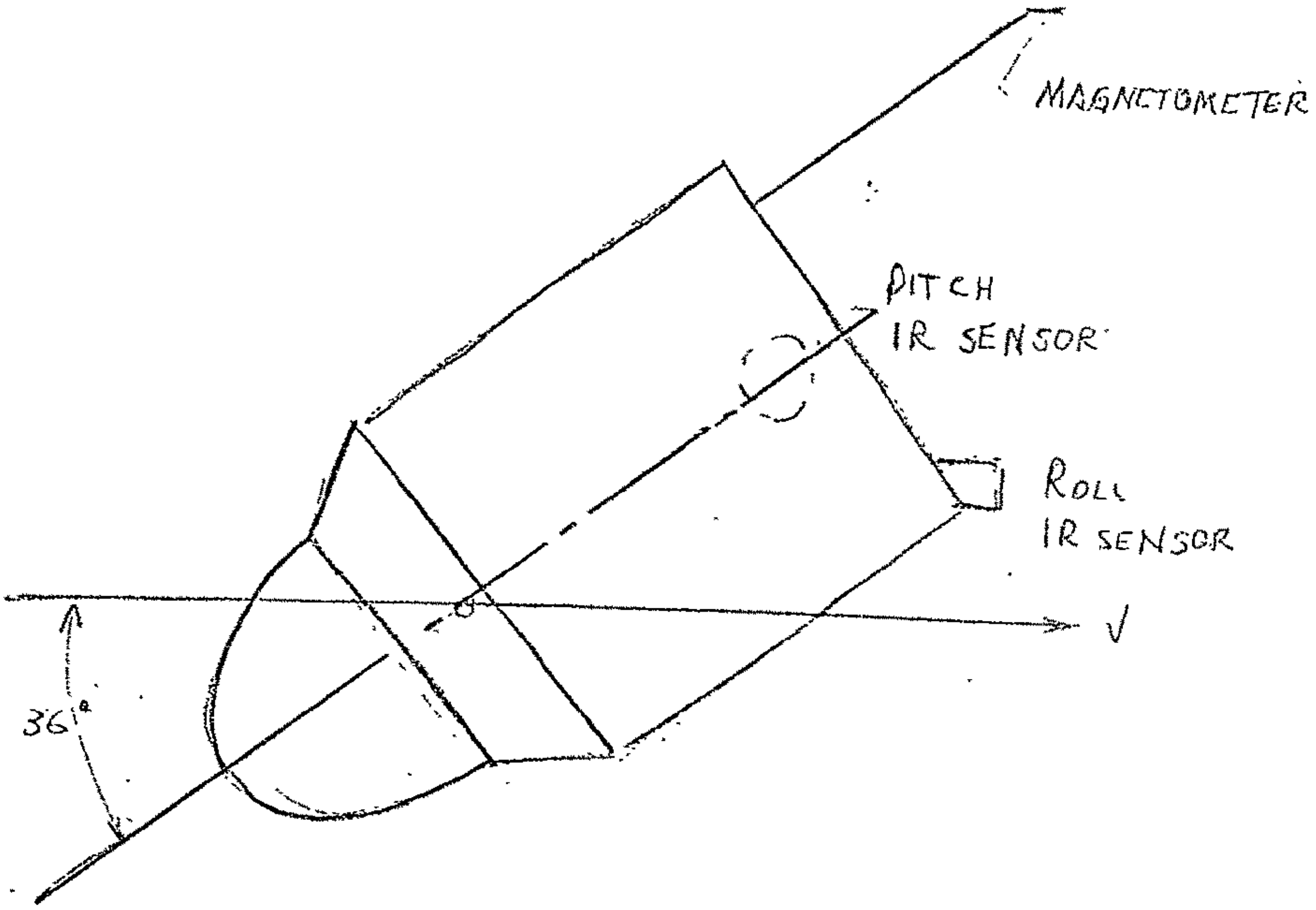


FIGURE NO. 8

HYBRID SIMULATION BLOCK DIAGRAM

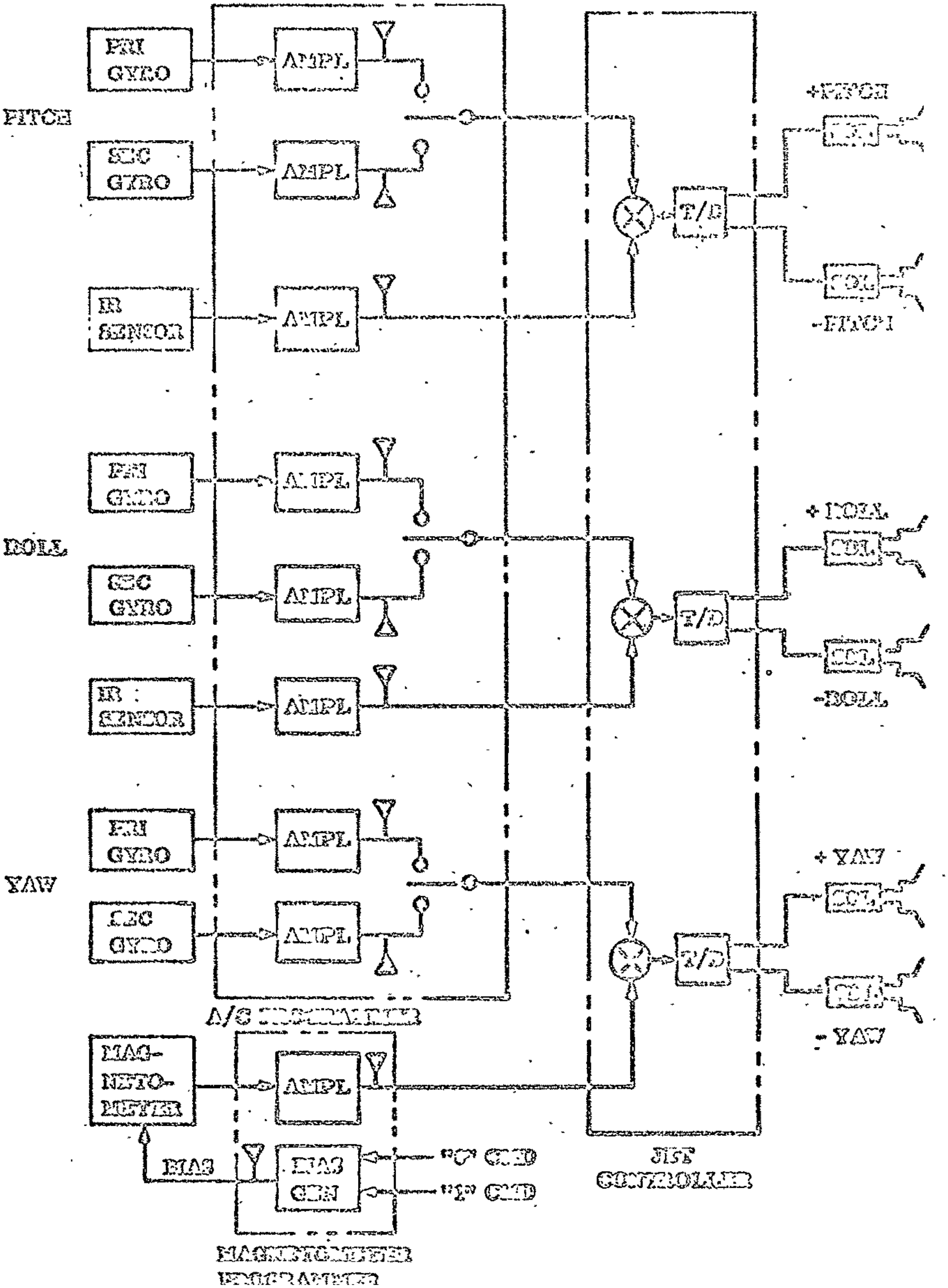
BIOSATELLITE SPACECRAFT IN DEORBIT ATTITUDE

FIGURE NO. 9



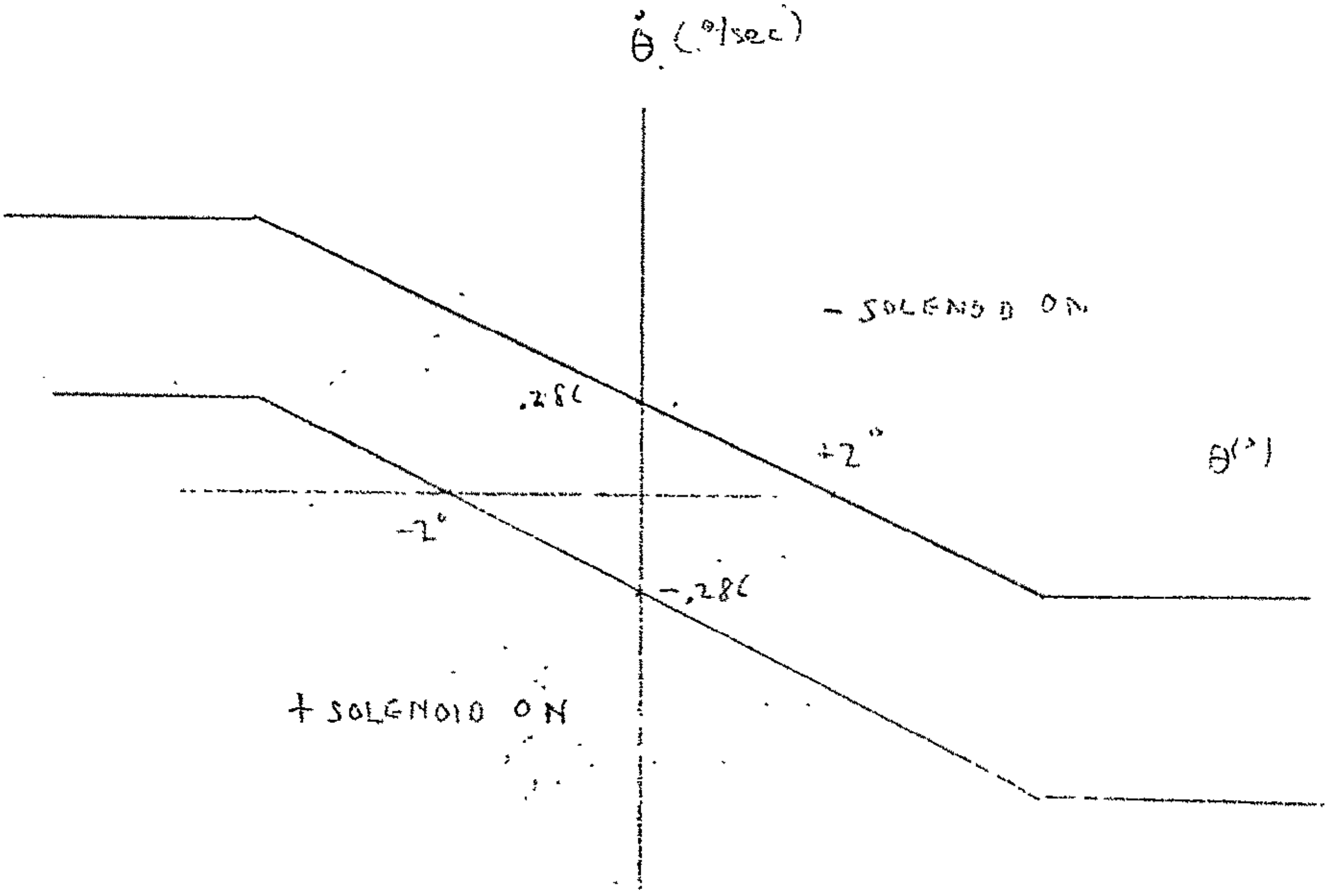
ACS DEORBIT MODE

FIGURE NO. 10



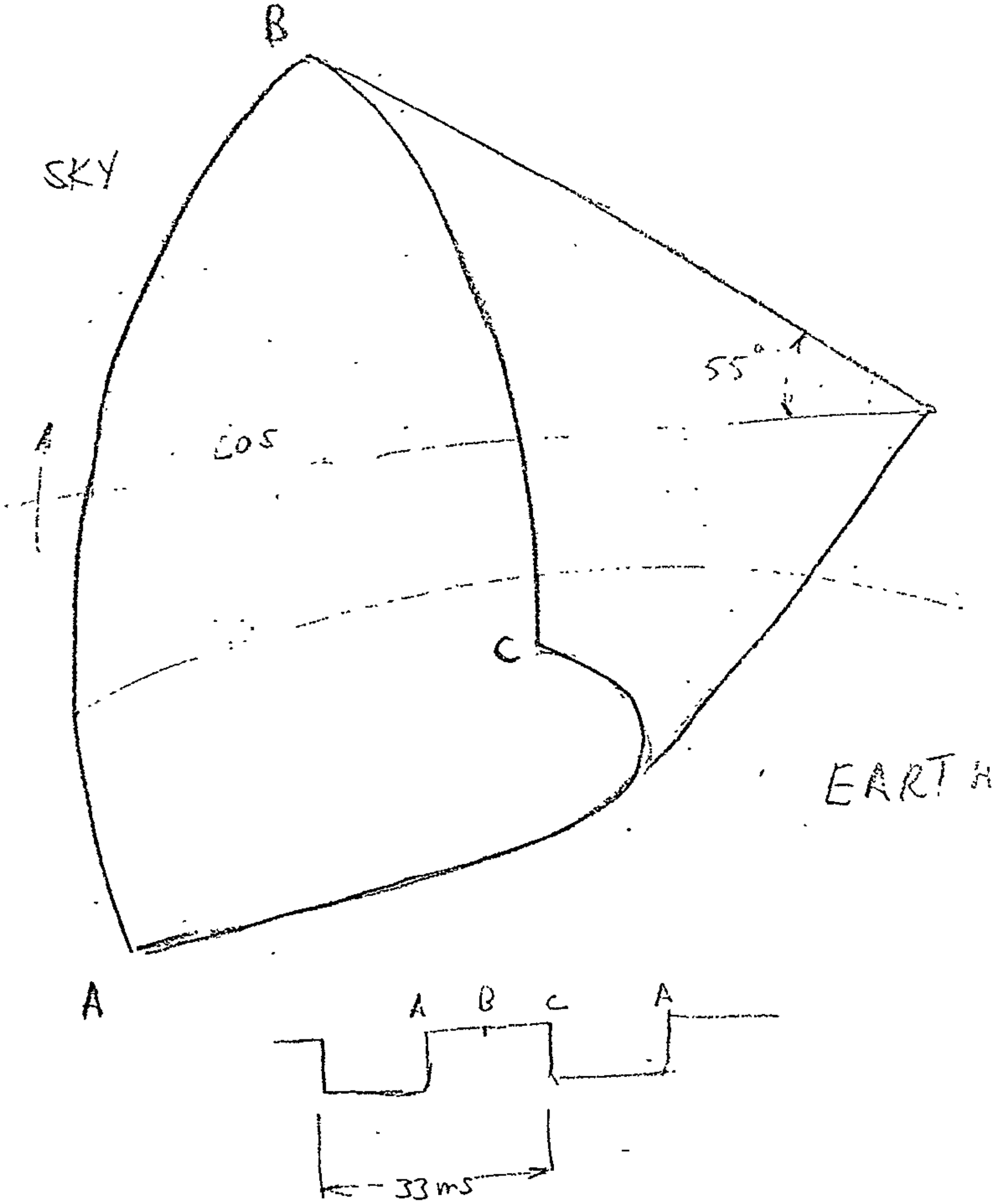
DEORBIT MODE SWITCHING LINE CONFIGURATION

FIGURE NO. 11



IR SENSOR/EARTH INTERFACE

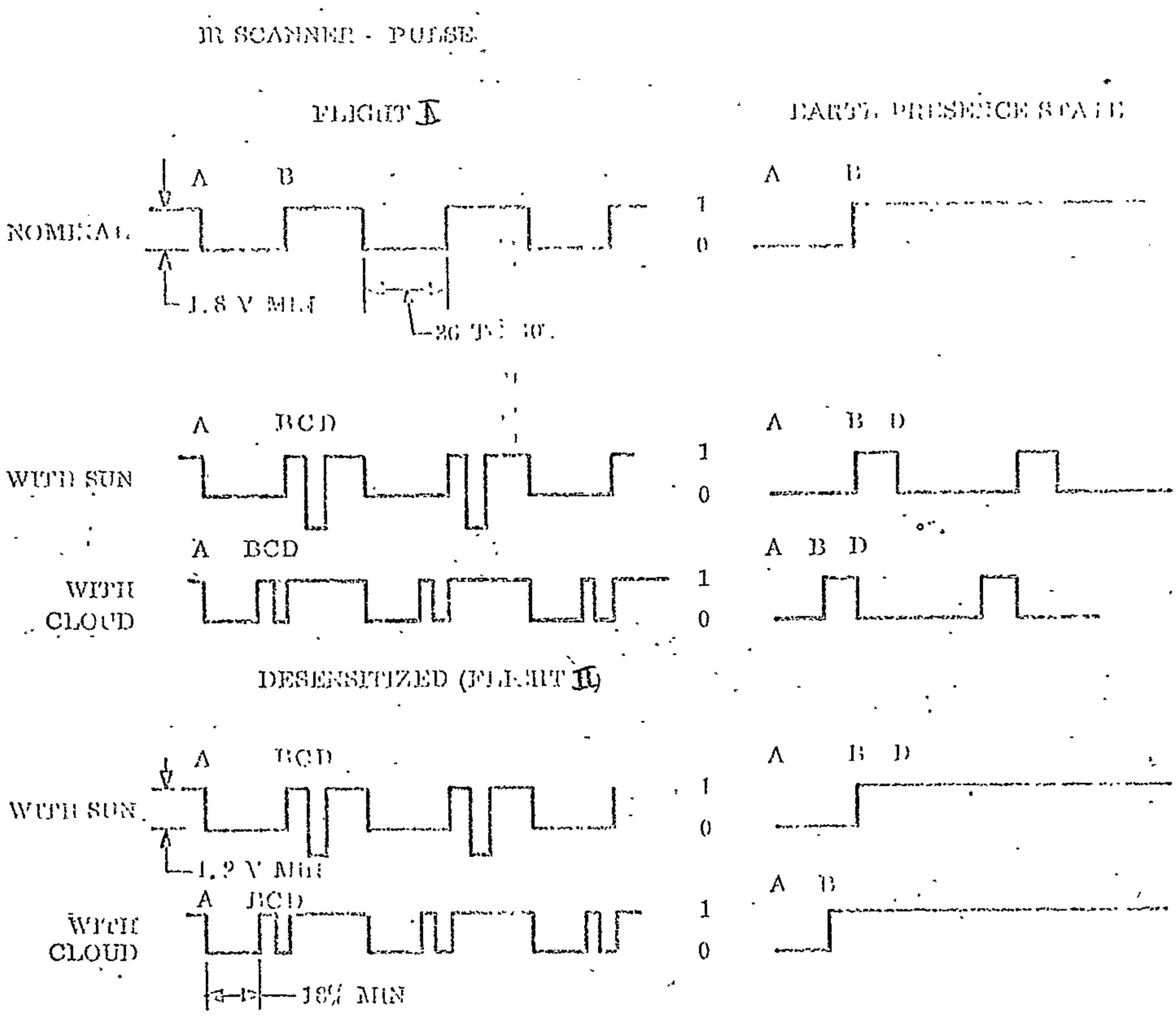
FIGURE NO. 12



SUN AND CLOUDS IN IR SENSOR FIELD OF VIEW

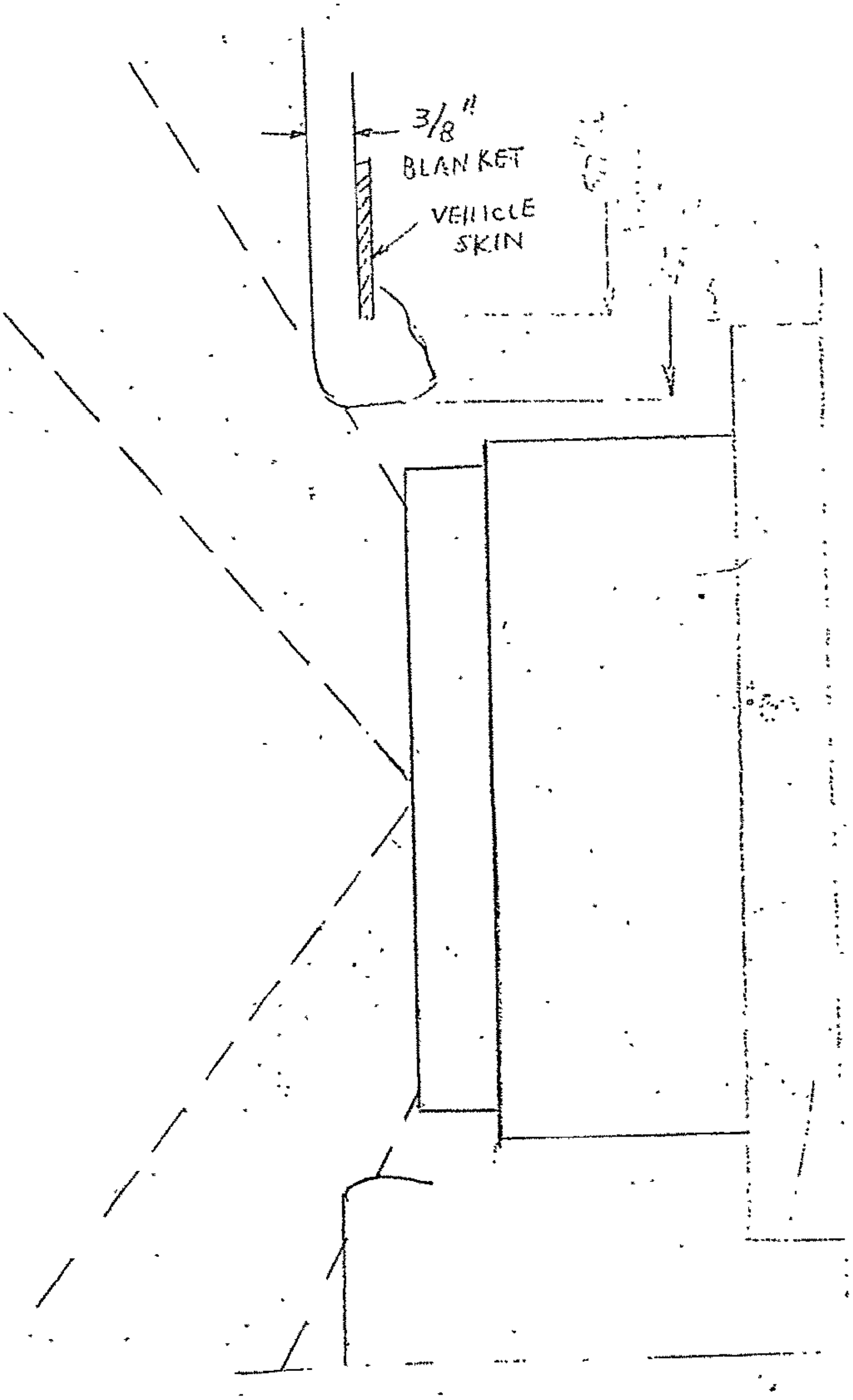
FIGURE NO. 13

EARTH PRESENCE LOGIC



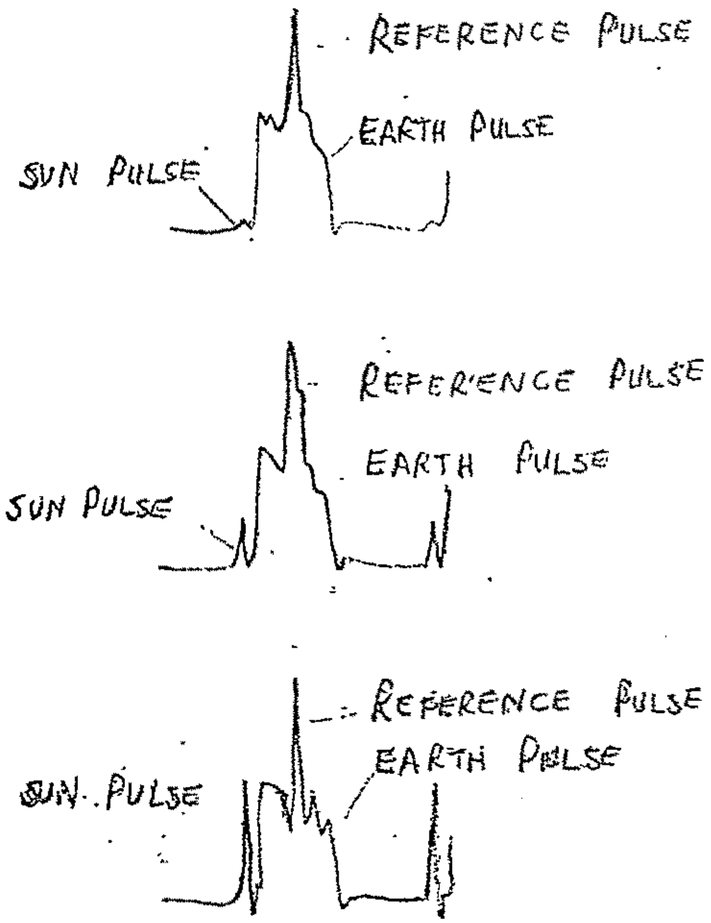
IR SENSOR/THERMAL BLANKET INTERFERENCE

FIGURE NO. 14



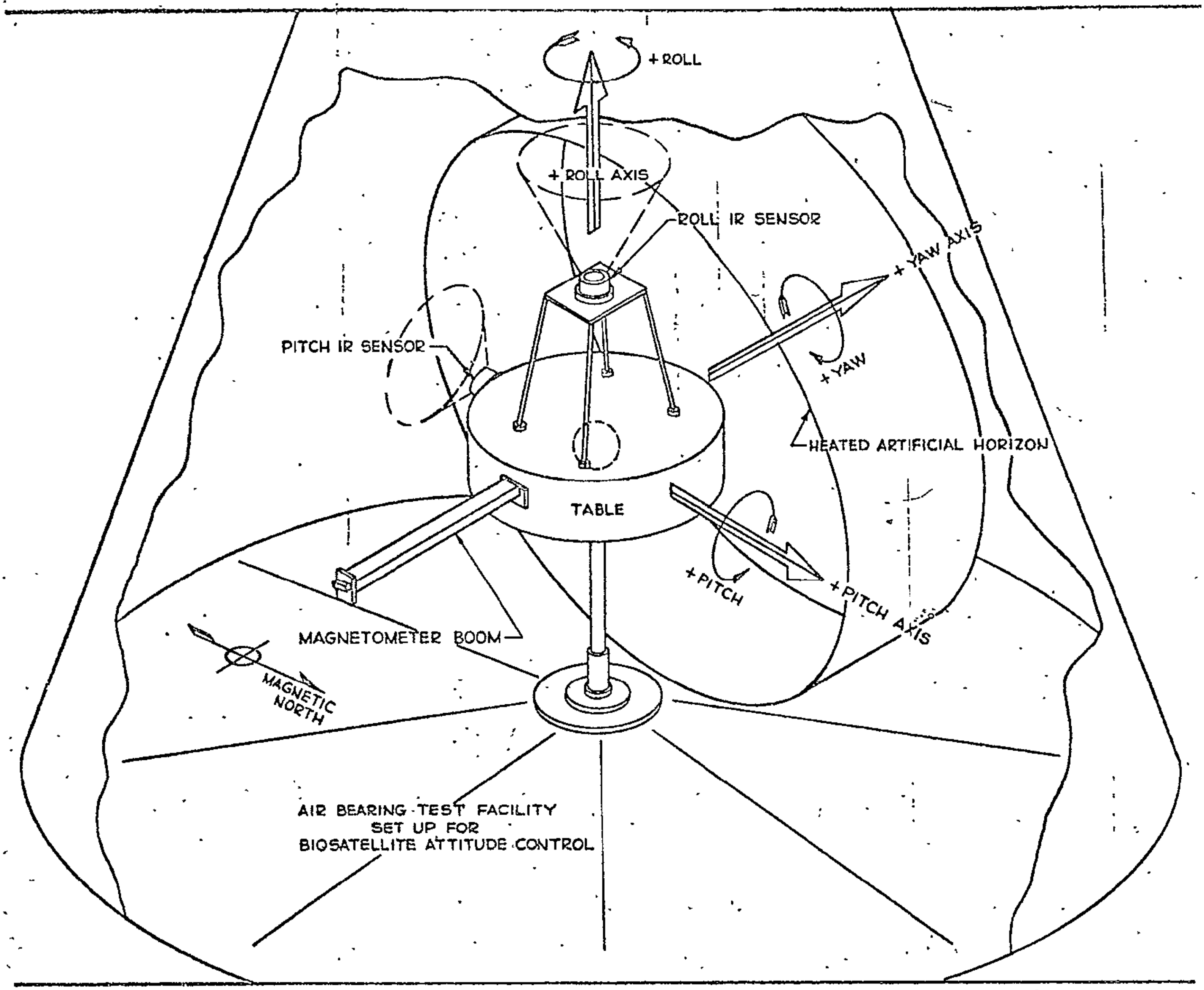
IR SENSOR DATA FROM BIOSATELLITE II

FIGURE NO. 15



THREE AXIS AIR BEARING SCHEMATIC

FIGURE NO. 16



THREE AXIS AIR BEARING SETUP

FIGURE NO. 17