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SKYLAB ATTITUDE AND POINTING CONTROL SYSTEM

by W. B. Chubb and S. M. Seltzer

George C. Marshall Space Flight Center
Marshall Space Flight Center, Ala. 35812

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16. ABSTRACT

NASA's Marshall Space Flight Center is developing an earth-orbiting manned space station called Skylab. The purpose of Skylab is to perform scientific experiments in solar astronomy and earth resources and to study biophysical and physical properties in a zero gravity environment. The attitude and pointing control system requirements are dictated by onboard experiments. These requirements and the resulting attitude and pointing control system are presented.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

DEFINITION OF SYMBOLS

$\overline{H}$	momentum vector
$\overline{H}_T$	total momentum vector
$\overline{H}_1, \overline{H}_2, \overline{H}_3$	momentum vectors associated with each of the CMG's
I_X, I_Y, I_Z	principal moments of inertia about the X, Y, and Z axes, respectively
K_{FS}	fine sun sensor gain
K_m	torquer gain
K_{RG}	rate gyro gain
K_α	amplifier gain
s	Laplace transform
T_C	commanded torque
T_D	disturbance torque
X, Y, Z	vehicle axes
α_j	angle between orbit normal and the jth momentum vector $\overline{H}_j$
$\dot{\delta}_{1(1)}, \dot{\delta}_{1(2)}, \dot{\delta}_{1(3)}$	gimbal rate about inner axis for jth CMG
$\dot{\delta}_{3(1)}, \dot{\delta}_{3(2)}, \dot{\delta}_{3(3)}$	gimbal rate about outer axis for jth CMG
ζ	rate gyro dumping ratio
τ_{FS}	fine sun sensor rise time
τ_α	amplifier rise time
ω_N	rate gyro natural frequency

SKYLAB ATTITUDE AND POINTING CONTROL SYSTEM

SUMMARY

NASA's Marshall Space Flight Center is developing an earth-orbiting manned space station called Skylab. The purpose of Skylab is to perform scientific experiments in solar astronomy and earth resources and to study biophysical and physical properties in a zero gravity environment. The attitude and pointing control system requirements are dictated by onboard experiments. These requirements and the resulting attitude and pointing control system are presented.

I. INTRODUCTION

The Skylab-A[1-3] is to be an experimental space station developed by the National Aeronautics and Space Administration. The Skylab program is an extension of the Mercury-Gemini-Apollo manned space flight programs and makes extensive use of hardware and technology developed in those programs. The purpose of the program is to increase our knowledge of manned space flight and to accomplish selected scientific, technological, and physiological investigations. The objectives of the program are:

(1) To conduct solar astronomy scientific experiments, emphasizing observations that cannot be obtained from earth because of absorption of certain electromagnetic waves by the atmosphere.

(2) To conduct earth resources experiments designed to permit an evaluation of existing technology and how it may be applied to aid in the solution of ecological problems. The need for further development of sensor technology will also be determined.

(3) To conduct biomedical experiments to determine the effect of long duration space flight on the crew.

The Skylab is being developed under the overall program responsibility of NASA's Office of Manned Spaceflight. The Marshall Space Flight Center, Huntsville, Alabama, has program management responsibility for developing all Skylab hardware except the Command and Service Module (CSM), for providing the launch vehicles, for flight evaluation, and for overall systems engineering to ensure compatibility and integration of all hardware. NASA's Manned Spacecraft Center in Houston, Texas, is responsible for modifying the CSM, for developing the spacecraft launch adapter (SLA), for developing the experiments and crew support equipment, for mission analysis and evaluation, and for astronaut crew training. The Kennedy Space Center in Florida will provide the launch facilities and execute the launches. Major contractor support for Skylab-A is indicated below:

(1) Saturn launch vehicles. Boeing Corp., Chrysler Corp., and McDonnell-Douglas Corp.

(2) Skylab-A

(a) Martin Marietta Corp.: cluster payload integration and management

(b) McDonnell-Douglas Corp.: orbital workshop and airlock module

(c) IBM: Apollo Telescope Mount (ATM) digital computers (primary and secondary) and workshop computer interface unit

(d) Bendix Corp.: control moment gyroscopes and electronics and experiment pointing electronic assembly

(e) North American Rockwell Corp.: modifications to the CSM

2. SKYLAB-A DESCRIPTION

The Skylab-A consists primarily of modules developed under the Apollo program and selected to meet the operational requirements of the Skylab-A program. The modules will be launched aboard Saturn launch vehicles, placed in an earth orbit, and assembled there. The Skylab-A (Fig. 1) consists of the following modules:

Orbital Workshop (OWS). The OWS is a modified empty S-IVB stage that will provide the astronauts with living quarters while in orbit. It will contain necessary food-preparation and waste-management facilities to support a three-man crew for the planned manned missions.
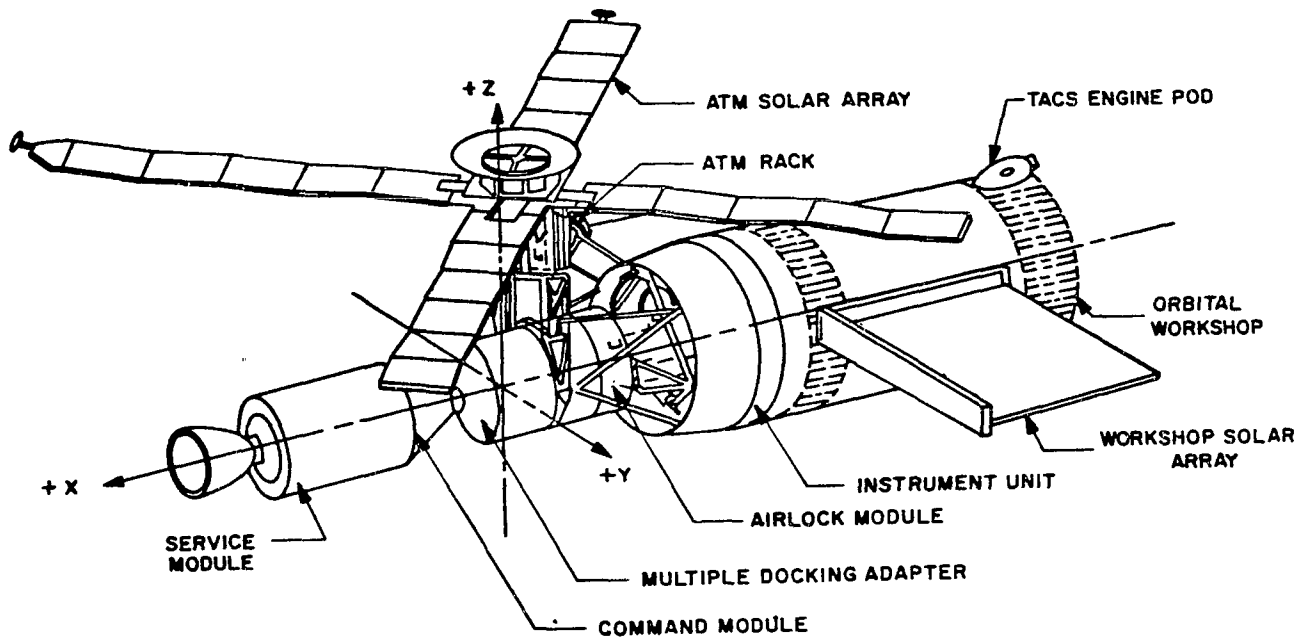
FIGURE 1. SKYLAB-A

Certain experiments and supporting facilities for their operation also will be contained in the OWS (see Appendix). Attitude control commands will be implemented by a cold-gas thruster attitude control system (TACS) located on the OWS. Two solar array panels attached to the sides of the OWS will provide some of the power required by the Skylab-A. The OWS will remain in orbit in unmanned storage modes and will be reactivated during subsequent manned revisits.

Multiple Docking Adapter (MDA) and Airlock Module (AM). The MDA and AM provide docking ports for the CSM and provide a pressurized passageway between the CSM and the living quarters in the OWS. The MDA contains the ATM control and display (C&D) panel. Experiments housed in these two modules are described in the Appendix; most of the experiments are included in the Earth Resources Experiment Package (EREP).

Apollo Telescope Mount (ATM). The ATM is to be a solar observatory developed primarily to collect data on solar phenomena to increase man's knowledge of the solar environment. It provides a mounting structure, or rack, to which are attached the control moment gyroscopes (CMG's), attitude control computers and sensors, and associated electronics. Within the rack an experiment spar is located to which are attached solar experiments and spar control sensors. The spar is gimbaled about two axes with respect to the rack. The ATM provides a capability for film retrieval and installation by astronaut extravehicular activity (EVA).

Solar Arrays. Two solar array panels are mounted on

each side of the OWS and four panels are attached to the ATM. Their purpose is to provide power for the Skylab-A system. The average power output of these combined arrays is approximately 7.2 kW.

Saturn V Instrument Unit (IU). The IU is used only during launch and for the subsequent seven and one-half hours of orbital operation while the CMG's are being brought up to operational speed (149 rev/s). Once in orbit, it provides sequencing commands to actuate and control the deployment of the Skylab-A elements. It also provides an IU digital command system and telemetry link with the ground.

Command and Service Module (CSM). The CSM provides the crew with transportation between the earth and the Skylab-A. It also contains food, water, and other essentials for crew support when the CSM is detached from the Skylab-A. The CSM provides some of the communication, instrumentation, and thermal control capability. It has the capability of providing attitude control to counteract transient responses to docking maneuvers through use of its reaction control system (RCS) which utilizes hypergolic storable propellants.

Experiments. The experiments are one of the primary reasons for development of the Skylab-A and dictate the attitude and pointing control requirements. A description of these experiments and their locations are provided in the Appendix.

3. MISSION IMPLEMENTATION

The unmanned Skylab-A, less the CSM, is placed in a

2

near-circular 435-km orbit with a nominal inclination of 0.87 rad by a two-stage Saturn V launch vehicle. Within the seven and one-half hours of IU lifetime, the Skylab-A ATM rack is oriented toward the sun, and the solar panels are deployed. The Skylab-A interior is then pressurized to make it habitable for the crew.

Approximately one day later the CSM, carrying a three-man crew, is placed into a temporary 150 x 222 km orbit by a Saturn IB launch vehicle. Using its own propulsion system, the CSM achieves a rendezvous with the remainder of the Skylab-A and docks to an axial port of the MDA. It is planned for the crew to remain onboard the Skylab-A for 28 days to conduct experiments. They then will prepare the Skylab-A for orbital storage and return to earth in the CSM on the 29th day. Two subsequent launches, similar to the second launch, are planned. Manned mission durations of no greater than 56 days are anticipated. The first two flights are planned for the last quarter in 1972.

4. SYSTEM REQUIREMENTS

The Skylab-A attitude and pointing control system has been developed to meet the high accuracy requirements established by the desired experiment conditions. These conditions must be maintained by the control system under the influence of external and internal disturbance torques, such as gravity gradient and aerodynamic disturbances and onboard astronaut motion. The Skylab-A attitude control system provides a stable base about which the ATM spar attitude control system may respond to meet higher frequency attitude control system demands. Hence, a fine pointing system, i.e., the experiment pointing system (EPS), for directing the experiment package on the ATM spar has evolved to meet the stringent experiment pointing requirements. The design requirements for each of the systems are listed in Tables I and II. Roll is defined as the angular

TABLE I. EPS CONTROL SYSTEM REQUIREMENTS

System Axis	Command Pointing Uncertainty	Stability for 15 Min
EPS X (pitch)	$\pm 1.1 \times 10^{-5}$ rad	$\pm 1.1 \times 10^{-5}$ rad
EPS Y (yaw)	$\pm 1.1 \times 10^{-5}$ rad	$\pm 1.1 \times 10^{-5}$ rad
EPS Z (roll)	$\pm 2.9 \times 10^{-3}$ rad	CMG control system

TABLE II. CMG CONTROL SYSTEM REQUIREMENTS

System Axis	Command Pointing Uncertainty	Stability for 15 Min
CMG X (pitch)	$\pm 1.2 \times 10^{-3}$ rad	$\pm 2.6 \times 10^{-3}$ rad
CMG Y (yaw)	$\pm 1.2 \times 10^{-3}$ rad	$\pm 2.6 \times 10^{-3}$ rad
CMG Z (roll)	$\pm 2.9 \times 10^{-3}$ rad	$\pm 2.2 \times 10^{-3}$ rad

rotation about the line of sight (LOS) from the experiment package to the center of the sun, and pitch and yaw are defined as angular deviations of the experiment

package with respect to the LOS. The requirements for the Z-local vertical (Z-LV) mode of operation (e.g., during earth resources experiments) are the same as shown in Table II except that a navigation error of $\pm 3.5 \times 10^{-2}$ rad is acceptable.

5. CONTROL SYSTEMS DESIGN PHILOSOPHY

The ATM pointing and control system that has evolved to date has been influenced by a number of factors.[4] The prime requirement is to meet the high accuracy system pointing specifications in the presence of external disturbance torques. The significant disturbance torques of interest are those caused by earth-orbital environmental influences (gravity gradient and aerodynamic disturbances) as well as internal movements of the astronauts on board. Because of these earth-orbital environmental influences, the vehicle attitude must be held to a fixed position relative to the orbital plane. To meet the pitch and yaw pointing accuracies, a two-axis gimbaled EPS with a maximum range of $\pm 3.5 \times 10^{-2}$ rad is required. The primary requirement for the EPS is to provide experiment package isolation from the relatively large vehicle perturbations that can result because of astronaut motion effects.

The CMG control system of the rack was chosen primarily because of performance benefits with respect to both dynamic response and compensation of cyclic external disturbance torques caused by gravity gradient and aerodynamic effects. Most passive control schemes (gravity gradient, for example) would not have the required accuracy and could not develop sufficient torque to meet the dynamic performance requirements. During data gathering intervals when experiment optics are exposed, use of CMG's prevents optics contamination that would result from reaction control thruster exhaust.

The TACS (and the RCS, if necessary) is available to provide coarse attitude control and CMG momentum desaturation capability (if needed). The TACS and CMG system must be capable of maneuvering the vehicle to a desired experiment observation orientation; i.e., Z-LV and solar inertial. It was also necessary to meet the maneuver requirements of the vehicle using the CMG system as much as possible to minimize TACS propellant consumption.

Control of Skylab-A as differentiated from control of the experiment spar mounted on Skylab-A may be accomplished by the CMG's alone, the CMG's in conjunction with the TACS (nested system), or the TACS alone. In addition, in an emergency situation and as a back-up for Z-LV maneuvers, the CSM reaction control system may be utilized.

Major control system design philosophy considerations were:

    (1) To use the CMG system to meet vehicle control and maneuver requirements whenever possible.

    (2) To minimize the action of noncyclic torques (bias torques) upon the vehicle. These torques arise from two sources. The first is that the major principal moments of inertia of the vehicle are not identical and the interaction of the gravity field upon these inertias produces a bias momentum accumulation of

approximately 600 Nms about the vehicle X axis over an orbital period. The second is a result of vehicle venting of waste gases and accounts for a bias momentum accumulation of from 500 to 1000 Nms about a non-specified vehicle axis.

(3) When in the solar inertial mode, to hold that axis (nearly the X principle) about which bias momentum accumulation is minimum in the orbit plane. This significantly reduces gravity gradient bias torques.

(4) Consistent with the long mission lifetime of 240 days, to eliminate all single point failures in the design.

(5) To provide maximum system operating flexibility in regard to sensor and computer selection.

(6) To provide automatic alert and caution and warning signals to the astronauts and the ground controllers of abnormal system operation.

(7) To provide through digital computer software the capability of testing and switching out malfunctioning equipment and switching in backup equipment.

6. CONTROL SYSTEM DESCRIPTION

The attitude and pointing control system (APCS) consists of the three basic systems: the CMG, the TACS, and the EPS. The first two systems may control the Skylab-A either separately or together in a nested configuration. The EPS system is used only for experiment spar control.

The CMG system is a momentum exchange control system. The momentum exchange devices are three orthogonally-mounted double-gimbaled CMG's; each has a stored momentum capability of 2700 Nms. The CMG cluster is shown in Figure 2 where $\delta_{1(j)}$ and $\delta_{3(j)}$ are the gimbal rates about the inner and outer axes, respectively, for the jth CMG; j — 1, 2, 3. The Skylab-A (Fig. 1) principal moments of inertia and mass data are presented in Table III.

TABLE III. PHYSICAL CHARACTERISTICS OF SKYLAB-A

I_x	=	$0.8862 \times 10^6 \ kg \cdot m^2$
I_y	=	$0.5835 \times 10^7 \ kg \cdot m^2$
I_z	=	$0.5753 \times 10^7 \ kg \cdot m^2$
Mass	=	$0.830 \times 10^5 \ kg$
Overall Length	=	36.1 m
S-IVB Diameter	=	6.58 m

The use of CMG's in the pointing and control of a large manned space station is new, and the problems associated with that type of system are unique and were unsolved. Some of the problems encountered in the development of the CMG control system include the following:

(1) An acceptable control law for use of the CMG's in control of the Skylab-A.

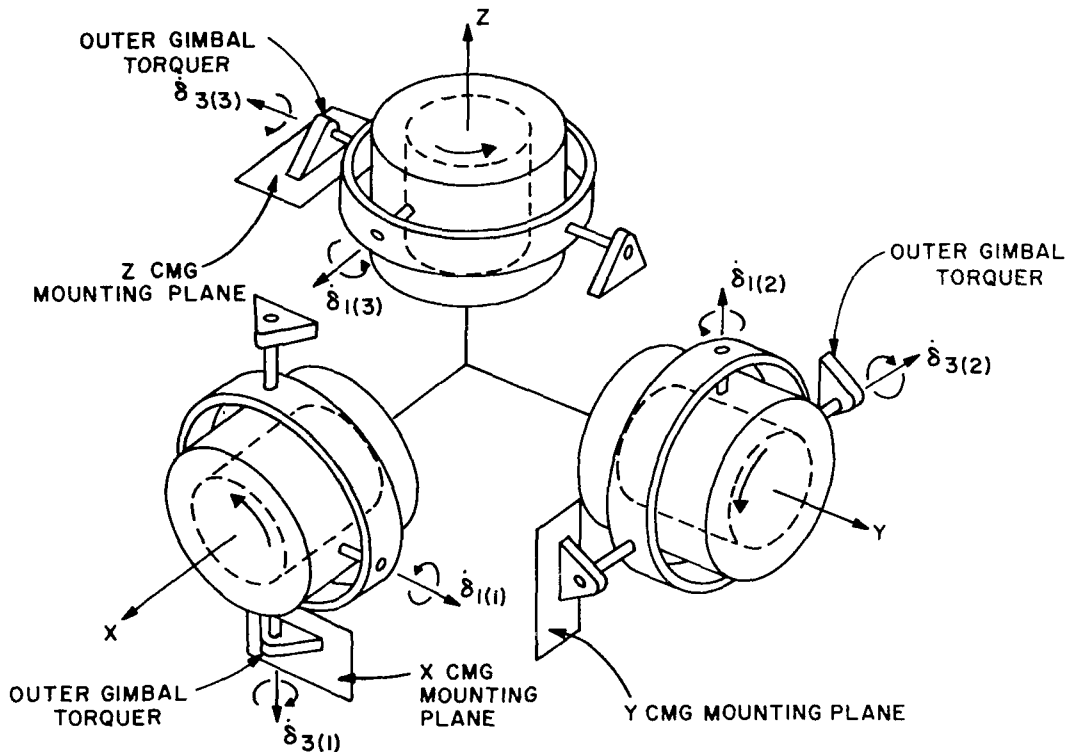(2) A means for preventing the CMG's from "falling

FIGURE 2. CMG CLUSTER

into" an undesirable orientation such as that which would not allow the use of the CMG's to control the spacecraft even though the CMG cluster was not in its saturation momentum state.

(3) A means of desaturating the CMG cluster periodically without the use of mass expulsion TACS. A method was needed to permit torques produced by an external force field such as gravity gradient to be used to effect CMG momentum desaturation.

(4) The optimal orientation of the vehicle to minimize external bias torques which would tend to saturate the CMG cluster; i.e., the placement of the minimum principal axis of inertia into the orbital plane.

An acceptable control law for use of the CMG's in control of the ATM cluster was developed. It can conceptually be broken down into three parts: the steering law, the distribution law, and the rotation law. A detailed derivation of these laws is given in Reference 5.

The function of the control law is to utilize three normalized torque commands together with the present orientation of the CMG's (in terms of their direction cosines) to generate inner and outer gimbal rate commands on each of the three CMG's. The steering law generates gimbal rate commands in such a way that (assuming the actual gimbal rates are equal to the commanded gimbal rates) the torques resulting on the vehicle are identical to the desired torques in direction and magnitude. Only when the maximum gimbal rate capability is exceeded will the magnitude of the resulting torque be less than commanded, but the direction will still be that of the command. No crosscoupling is inherent in the control law.

Only three degrees of freedom are utilized by the steering law. The remaining three are used by the other two laws. Because the bulk of the CMG momentum change is along the orbit normal, the distribution law tries to make the components of the CMG vectors along the orbit normal equal to each other. This has the effect of spreading the vectors, which in turn reduces the angular velocity required of the vectors to meet the needed momentum change. It also prevents the CMG's from falling into the undesirable anti-parallel orientation illustrated in Figure 3. The distribution is made by rotations about vector sums of pairs of individual CMG momentum vectors and thus does not affect the total momentum; i.e., no disturbance torques are transmitted to the vehicle as a result of application of the distribution law. Figure 4 is a simplified diagram illustrating this principle. No distribution is necessary for two-CMG operation.

The rotation law utilizes only rotations about pair sums and total angular momentum is not disturbed (no torque on the vehicle). The angular velocities for the rotations are generated such that the largest gimbal angles are reduced, thus avoiding (as much as possible) hitting of the gimbal stops. The gimbal angles are weighted by their fifth power such that the distribution law is predominant for small gimbal angles and the rotation law is predominant for large gimbal angles. For two-CMG operation (no distribution law) the first power of the angles is used.
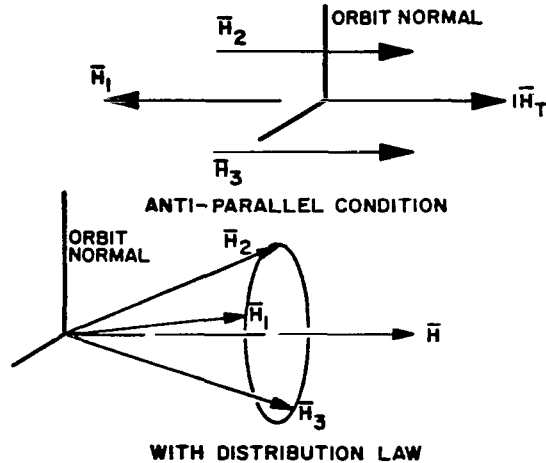

FIGURE 3. MOMENTUM VECTOR CONFIGURATION

ROTATE $\bar{H}_1$ AND $\bar{H}_2$ ABOUT $\bar{H}_1 + \bar{H}_2$ UNTIL EQUAL COMPONENTS OF $\bar{H}_1$ AND $\bar{H}_2$ LIE ALONG THE ORBIT NORMAL (i.e. $\alpha_1 = \alpha_2$)
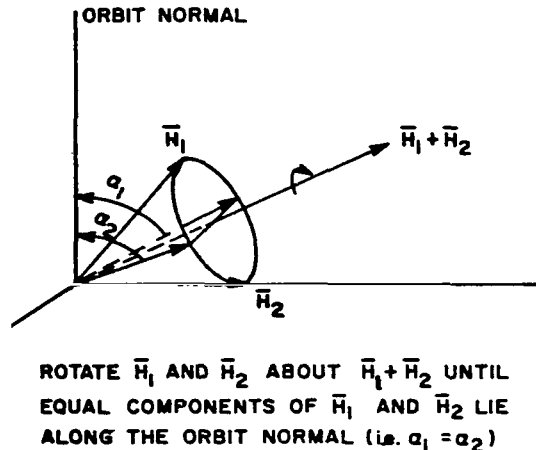
FIGURE 4. DISTRIBUTION LAW PRINCIPLE

To desaturate the CMG cluster periodically, without the use of the mass expulsion TACS, a method was developed utilizing the earth's gravity-gradient force field to effect CMG momentum desaturation. This method is described in detail in Reference 6. The basic concept is best described with the aid of Figure 5 which depicts the per orbit momentum build-up of the CMG cluster caused by gravity gradient and aerodynamic torques. This figure reveals that if periodic CMG desaturation was not provided, the CMG cluster would be saturated for progressively larger portions of an orbit after the first orbit. The axis of saturation would be roughly the vehicle X axis. This means that after complete saturation, the CMG cluster could not compensate for a disturbance torque about the axis of saturation.

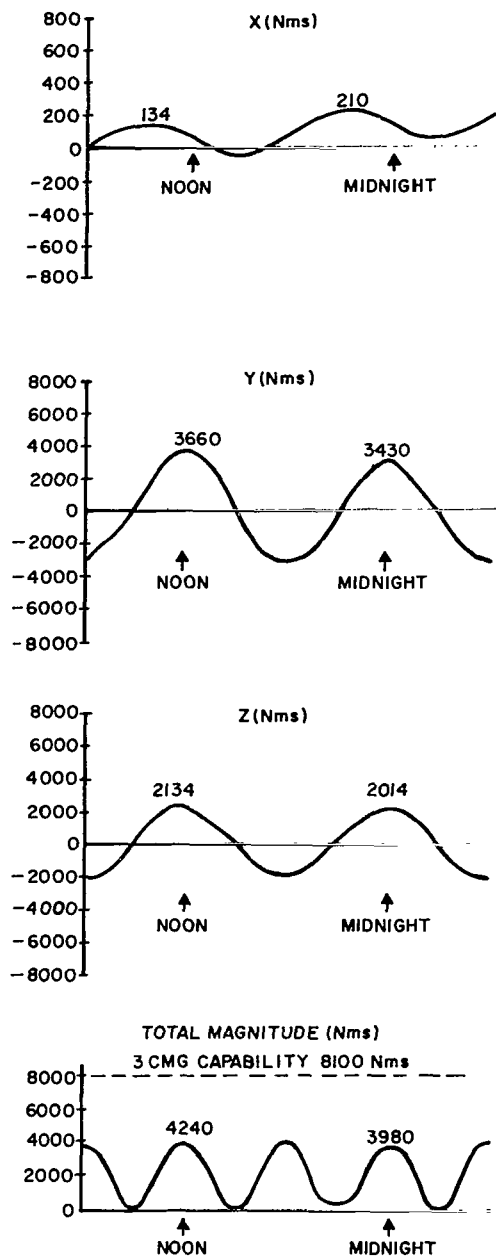An investigation of the causes of the predominant non-cyclic torques (i.e., gravity gradient and aerodynamic)

5

X (Nms)

134   210

NOON   MIDNIGHT

Y (Nms)

3660   3430

NOON   MIDNIGHT

Z (Nms)

2134   2014

NOON   MIDNIGHT

TOTAL MAGNITUDE (Nms)
3 CMG CAPABILITY 8100 Nms

4240   3980

NOON   MIDNIGHT

FIGURE 5. COMBINED DISTURBANCE IMPULSE

reveals that with the given vehicle configuration and mission requirements (i. e. , point the vehicle Z axis at radiometric center of sun every daylight period), it is impossible to eliminate the noncyclic torques, but it is possible to minimize them.

This problem of CMG momentum management was attacked in two separate ways.

(1) The noncyclic disturbance torques were minimized by finding an optimal vehicle orientation while still meeting the requirement that the vehicle Z axis point to the center of the solar disk. This was accomplished by sampling the vehicle momentum at specified times during the daylight orbital period and comparing it with the previous day's samples. The compared samples indicated whether the bias momentum components about the various vehicle axes were increasing or decreasing. This information was then translated into appropriate angle position commands about the vehicle Z axis to ensure minimization of bias momentum accumulation.

(2) The saturation effects of the remaining noncyclic disturbance torque were nullified by periodically producing controlled bias torques which would tend to desaturate the CMG cluster. The controlled bias torques are produced by employing rectified components of the gravity gradient torques encountered during the night portion of the orbit to desaturate the CMG cluster. The rectification of the gravity gradient torques is made possible by maneuvering the vehicle about two axes during the night side of the orbit. The magnitude of the maneuver angles is a function of the momentum accumulation during the daylight portion of the orbit.

The TACS is composed of six cold-gas thrusters and the necessary logic to select and fire the proper thruster. The thrusters are mounted as shown in Figure 6.

The thruster force is dependent upon the cold-gas tank pressure and will be approximately 45 kg at the beginning of the mission and diminish to about 4-1/2 kg at the end of the mission. The minimum impulse bit will be maintained at a constant level within the bounds of the selectable thruster firing time (40 to 400 ms).

A functional block diagram of the CMG system and TACS is shown in Figure 7. System information is available from two sources, the acquisition sun sensors or the strapdown equations which utilize rate gyro information as their basic input. Sensors as well as the basic digital computer are redundant to provide increased system reliability over the 240-day mission. Rate information is provided by rate gyros. The gyros have a coarse scale of $\pm 1.7 \times 10^{-2}$ rad/s and a fine scale of $\pm 1.7 \times 10^{-3}$ rad/s. The scale is selected by logic within the operating digital computer.

The ATM digital computer (ATMDC) is the primary data processing, computational, and logic generation facility in the control system. Fast loop computations (e. g. , rate gyro processing and CMG control laws) are performed at a rate of five times per second, and slow loop computations (e. g. , orbital navigation) are performed at a rate of one time per second. The computer memory capacity is 16,300 words with lengths of 16 bits. Present estimates of computer memory requirements are approximately 15,500 words. The ATMDC is the "brains" of the system and performs the following primary APCS functions.

(1) Orbital navigation and timing

(2) Control of operational modes

(3) Maneuver generation commands

(4) CMG and TACS control

(5) CMG momentum desaturation commands

(6) System redundancy management (test and selection of alternate vehicle components in the case of off-nominal component or system operation).
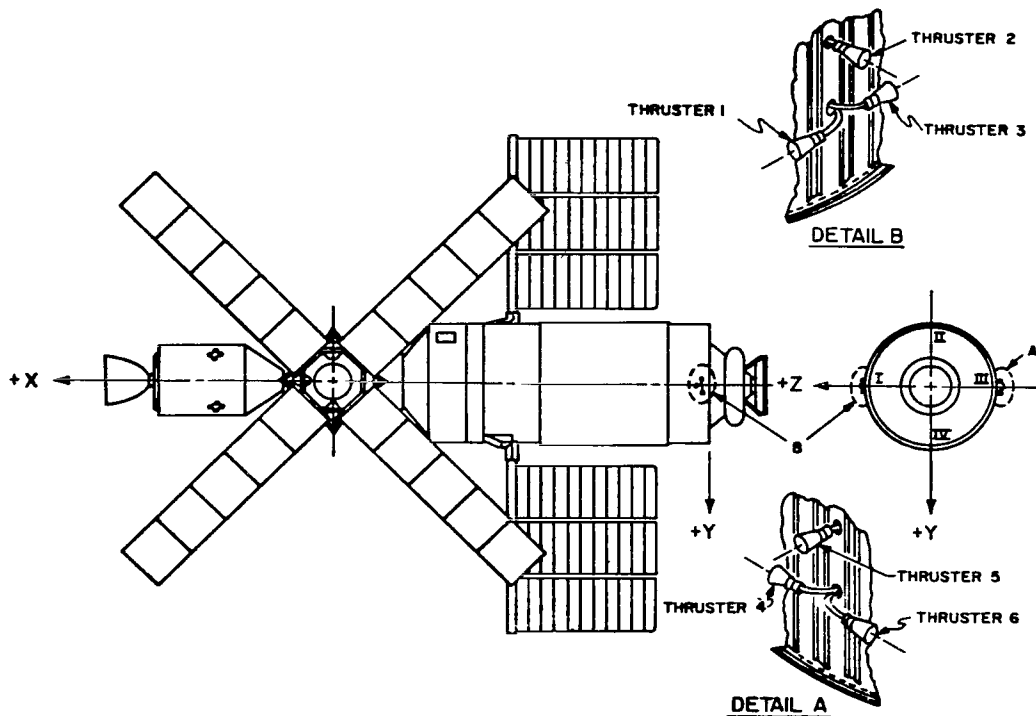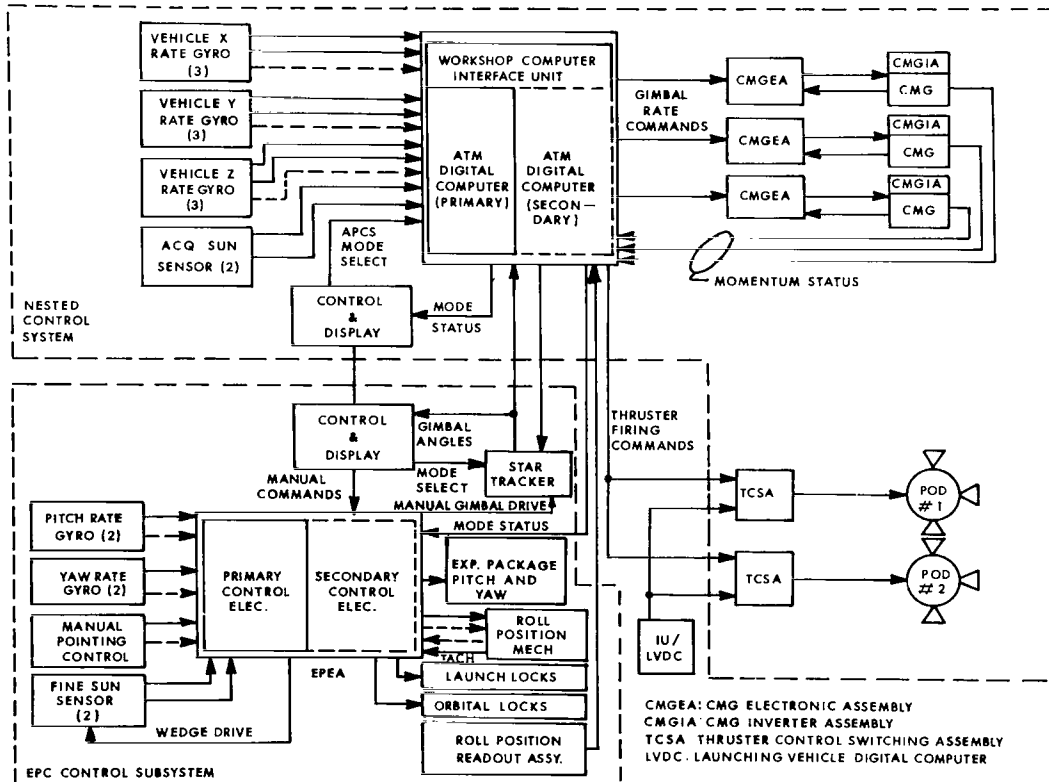
6

FIGURE 6. TACS THRUSTERS

CMGEA: CMG ELECTRONIC ASSEMBLY
CMGIA: CMG INVERTER ASSEMBLY
TCSA THRUSTER CONTROL SWITCHING ASSEMBLY
LVDC. LAUNCHING VEHICLE DIGITAL COMPUTER

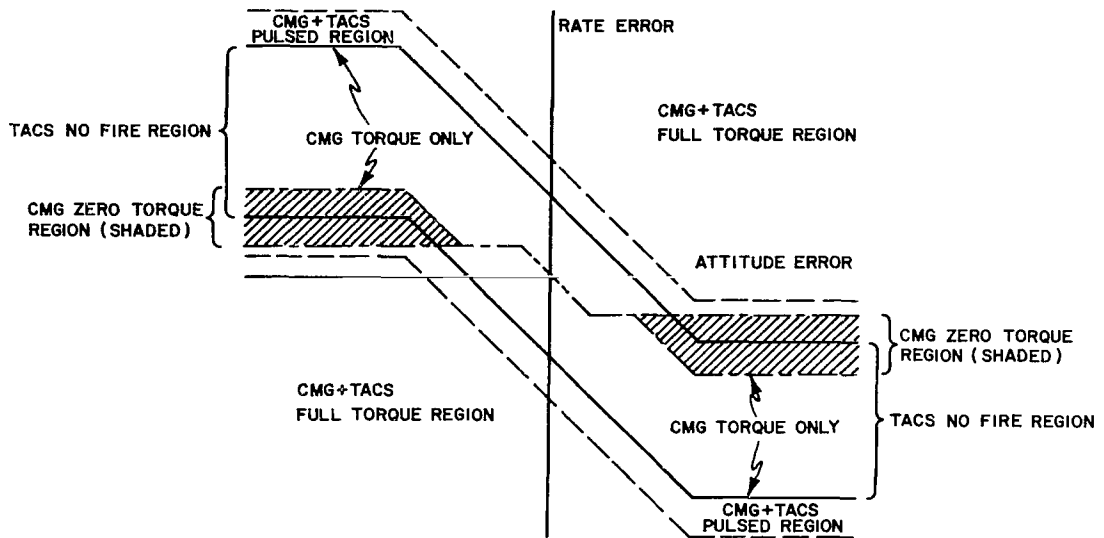FIGURE 7. FUNCTIONAL BLOCK DIAGRAM OF THE ATTITUDE AND POINTING CONTROL SYSTEM

FIGURE 8. PHASE PLANE DIAGRAM (NESTED CONFIGURATION)

While the CMG system and TACS may operate independently of each other, the nominal mode of operation is in a "nested" configuration. Figure 8 is a phase plane diagram of this type of system operation. All control is delegated to the CMG system as long as it has the capability of maintaining the attitude and rate error within the "no fire region" of the phase plane. If the attitude or rate error exceeds this region, the TACS supplies supplemental control authority until the vehicle attitude and rate errors are again within the "no fire region." A CMG inhibit region has been established on the phase plane to prevent the situation where the TACS and the CMG's would produce opposing torques. If the state of the vehicle lies in both the CMG zero torque region and the TACS no fire region, the attitude rate (which remains constant in this zone) will cause the attitude error to decrease until the vehicle state leaves the zone. The TACS, in addition to bounding the magnitude of the rate and position errors, also performs a CMG momentum desaturation function in the "nested" mode of operation. If the CMG total momentum vector exceeds 95% of the CMG capability, the digital computer directs those TACS engines to fire which will most efficiently cause the total momentum vector to fall below 95%. An example of this type of operation is illustrated in Figure 9.

The EPS operates independently from the CMG system and TACS. It has its own sun sensors and rate gyros for position and rate control. Control signals are generated in the experiment pointing electronic assembly (EPEA), an analog device.

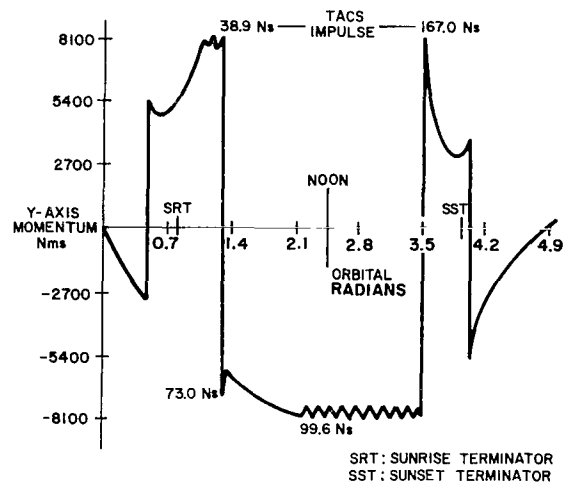The EPS utilizes flex-pivot* gimbal bearings for control about two axes and an open-loop positioning device to

FIGURE 9. Z-LOCAL VERTICAL MANEUVER IN CMG/TACS NESTED CONFIGURATION

meet positioning requirements about the third axis. The flex-pivots allow about $\pm 3.5 \times 10^{-2}$ rad of rotation of the X and Y axes while the roll positioning device allows for a rotation of ± 2.1 rad about the experiment package Z axis. Figure 10 shows a block diagram of this system.

While the EPS provides automatic control of the experiment package X and Y axes, manual positioning of these

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*A flex-pivot gimbal bearing is made of a pair of flat cross-leaf springs and is welded to and supported by rotating sleeves. It has no backlash and provides limited angular travel.
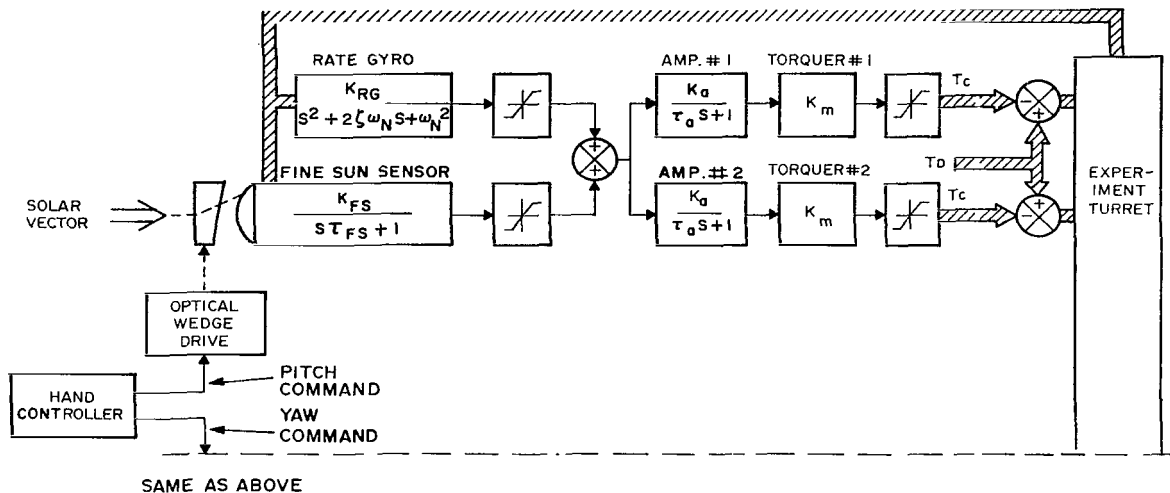
8

FIGURE 10. EXPERIMENT POINTING SYSTEM (EPS)

two axes is provided for the purpose of offset pointing. Fine sun sensors (FSS) are used for sensing spar attitude errors, with rate gyros sensing spar rates. The EPEA conditions the sensor's signals to provide rate plus displacement command signals to the flex-pivot actuators (dc torque motors).

The experiment package can be offset pointed in the X and Y axes over a range of $\pm 5.8 \times 10^{-3}$ rad, with the center of the solar disk being the zero position. The solar disk measures approximately $\pm 9.3 \times 10^{-3}$ rad from limb to limb. Offset pointing is accomplished by positioning an optical wedge located in each FSS. The wedge is mounted in the path of the sunlight passing through the FSS optics and can be rotated to refract the sunlight a fixed angle in a controlled direction. The wedges are positioned by a drive mechanism controlled by the astronaut via the manual pointing controller. The wedge drive varies from $\pm 6.5 \times 10^{-4}$ rad/s near zero offset positions to $\pm 3.7 \times 10^{-4}$ rad/s for wedge positions near the $\pm 5.8 \times 10^{-3}$ rad sun offset position. A wedge offset produces an FSS output error voltage that causes the spar to rotate about the appropriate axis (X or Y) and point the FSS, and thereby the experiment package, in a direction that will drive the FSS output voltage to null. Stability is then automatically maintained by the EPS. The experiments are aligned to the FSS. The position of each FSS wedge is displayed on the C&D panel and corresponds to the experiment package offset position from the center of the sun in the X or Y axis. The panel also contains television displays of the sun, as viewed through experiment telescopes, and experiment readout displays to assist the astronaut in pointing the experiment package.

The roll positioning mechanism (RPM) is used to rotate the spar about the Z axis. The mechanism is commanded by the astronaut via the manual pointing controller (rate switches) located on the control and display panel. Spar roll rates of $\pm 1.2 \times 10^{-1}$, $\pm 6.1 \times 10^{-2}$, $\pm 1.2 \times 10^{-2}$, and $\pm 6.1 \times 10^{-3}$ rad/s can be commanded. Once the spar is

positioned, the RPM will hold the location until a repositioning command is received. The astronaut repositions the spar in accordance with experiment demand requirements. The spar roll position is displayed on the C&D panel.

7. SYSTEM OPERATION

The APCS may be required to operate in any one of six mutually exclusive primary modes. These modes are configured to allow the APCS to perform its required tasks. The request for mode changes may come from one of three sources: (1) via switches on the flight crew's C&D panel, (2) by way of an onboard digital address system (DAS), and (3) from the ground-operated digital command system (DCS). Selected mode changes are also made within the digital computer as a function of sensor information and component redundancy management considerations. The primary operational modes are as follows:

Stand-By Mode: In this mode the ATMDC will not be processing output commands to the CMG system or the TACS. This mode will be used if no vehicle control is required of the APCS. With the exception of inhibiting the commands to the TACS and CMG system however, all normal ATMDC functions will be enabled. If the stand-by mode exists at the time of a computer switchover, this mode will be maintained.

Solar Inertial Mode: In this mode the "nested" CMG system and TACS will be used for vehicle control. The vehicle Z axis is pointed toward the center of the solar disc. The vehicle X axis lies nearly in the orbital plane but is oriented so that it is consistent with minimum bias momentum accumulation considerations and points in the direction of the earth at the morning terminator. The vehicle Y axis forms a right-handed triad. The ATMDC will obtain attitude information for inputs to the control law as follows:

9

(1) Orbital Day: The ATMDC will use the acquisition sun sensor for X and Y axes attitude information and the strapdown computation for Z axis attitude information. The rate gyro outputs will be used for rate stabilization in all three axes.

(2) Orbital Night: The ATMDC will use the strapdown computation for X, Y, and Z axes attitude information and the rate gyros for rate stabilization.

Momentum management desaturation maneuvers will be performed during the night periods. Automatic entry into the solar inertial mode occurs when the APCS is in the experiment pointing mode (day operation) and the crew does not exit the mode manually prior to orbital sunset. This mode will also be entered at the time of a computer switchover, unless the mode existing at that time is the stand-by mode.

Experiment Pointing Mode: The experiment pointing mode is identical to the day portion of the solar inertial mode, with respect to vehicle control. In this mode, however, the EPS will be activated. Normally, the experiment pointing mode will be entered manually, with automatic exit at orbital sunset. Automatic entry is also provided as an option to be activated by the crew via DAS command. The crew will be able to enable or inhibit automatic experiment pointing mode entry at will. If the crew has enabled automatic entry, the ATMDC will activate the mode each orbital sunrise, if and only if the system is in the solar inertial mode the preceding night period.

CMG Nested Attitude Hold Mode: The vehicle will be under nested CMG/TACS control in this mode and will be maintained in an inertial hold. The ATMDC will use the strapdown computation for attitude information in X, Y, and Z, and the rate gyro outputs for rate stabilization. The momentum management maneuvers will be inhibited in this mode. No provisions exist for automatic entry to or exist from this mode. Manual vehicle attitude commands may be entered in this mode via DAS. The attitude is not limited, but the maneuver rate is limited to $\pm 5.2 \times 10^{-3}$ rad/s.

TACS Attitude Hold Mode: This mode will be an inertial hold mode, random attitude, with the TACS in control. As in the attitude hold mode, the ATMDC will obtain attitude and rate information from the strapdown computation and the rate gyros. No provisions exist for automatic entry to or exit from this mode; and the attitude is not limited, but the maneuver rate is limited to $\pm 5.2 \times 10^{-3}$ rad/s.

Z-Local Vertical (Z-LV) Mode: This mode will be used for earth pointing experiments during the manned periods and for rendezvous during the unmanned periods. The vehicle will be under CMG/TACS control in this mode. The mode will have two sources of activation. For earth resources experiments, the crew will command the ATMDC via the C&D panel switch to enter the Z-LV mode. At that time the ATMDC should start the maneuver to Z-LV. The elapsed time from initiation of the maneuver until the Z-LV attitude is reached will be a stored value in the ATMDC, addressable by the crew via the DAS. Figure 11 illustrates a typical
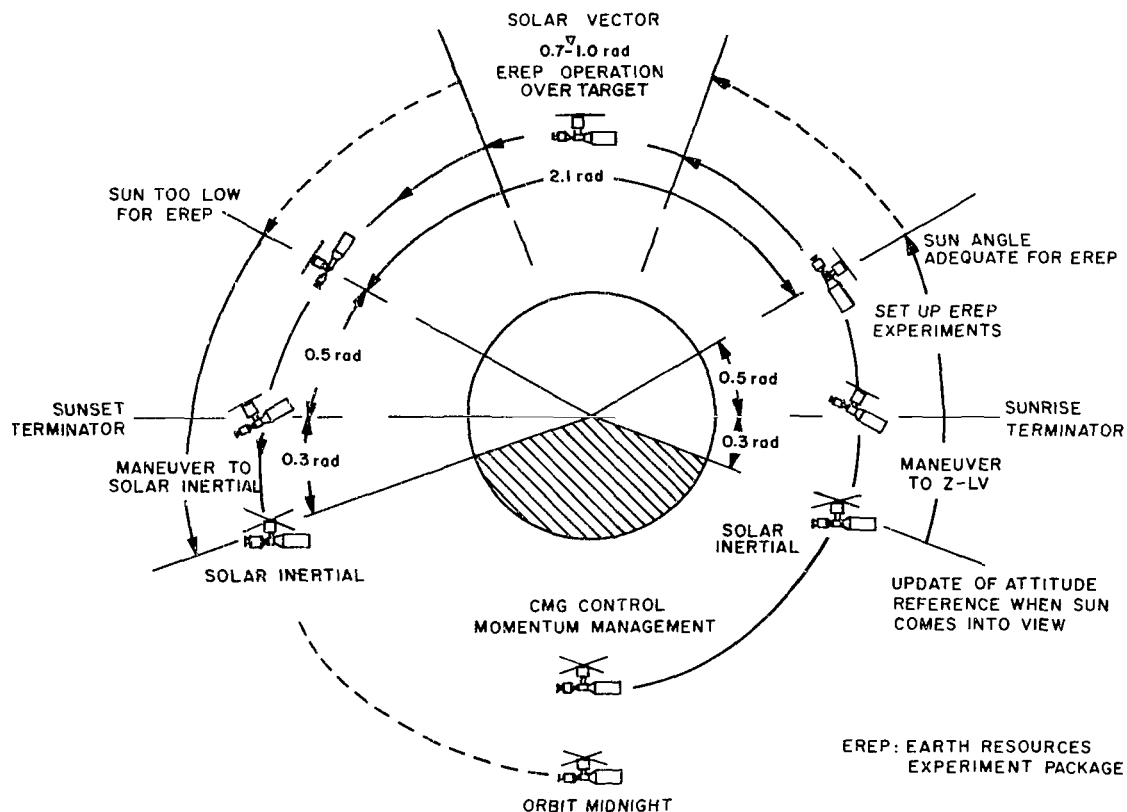

FIGURE 11. EARTH RESOURCES MANEUVER SEQUENCE

Z-LV earth resources maneuver sequence. For rendezvous, both the time for initiation and the time for completion of the Z-LV acquisition will be specified. In this case the ground will command the mode change. Leaving the Z-LV mode will be similar; it may be commanded either by crew command (C&D switch) or ground (relative to time).

Mode Options: Several somewhat unrelated "submodes" will be available, primarily for the crew, for altering certain operational aspects of the APCS. Again, the states of these submodes may be changed by crew command, ground command, or ATMDC program control. The submodes include inhibiting automatic gravity gradient desaturation maneuvers, inhibiting CMG or TACS control, switching the navigation timing sequence from a computational procedure to one based on sun present discretes, and the capability of performing a preprogramed set of maneuvers to reacquire the solar vector should the system suffer a temporary loss of attitude information.

Hybrid simulations of the Skylab attitude and pointing control system at Marshall Space Flight Center have been in operation for the past eighteen months. In general, simulated results have been in agreement with theoretical predicted results. In those instances where predicted and actual results have differed, the simulation models have been used as design tools to correct digital logic to eliminate or minimize these differences. One area where inconsistent results were noted concerned gimbal angle stops. Inner gimbal

CMG stops are located at ±1.4 rad and outer stops are at +3.8 and -2.3 rad. These physical constraints limited total CMG momentum utilization whenever the stops were encountered. Special digital logic was developed to minimize the number of situations when CMG gimbal stops would be encountered.

A document[7] describing in detail the ATM digital computer program requirements has been prepared by NASA and recently updated[8] for NASA by IBM. Included in this document are detailed requirements and implementation schemes in analytical form for functions such as momentum management, CMG momentum distribution, CMG control laws, TACS logic, vehicle attitude reference (strapdown), and APS mode control.

8. CONCLUSIONS

Based on the mission and high accuracy experiment pointing requirements, the design of the Skylab-A attitude and pointing control system has been developed. A significant portion of the system is capable of manual operation, enabling the astronauts to perform functions requiring human judgment, such as choosing scientific targets and selecting and pointing appropriate experiments toward these targets. To keep the number of tasks to be performed by the astronauts within reason, many functions such as attitude pointing stability are performed using closed loop automatic control.

APPENDIX
SKYLAB EXPERIMENTS*

Experiments Located in the Apollo Telescope Mount

White-Light Coronograph (S052): Use an externally occulted coronograph to monitor, in the 4000 to 6000 A range, the brightness, form, and polarization of the solar corona from 1.5 to 6 solar radii.

X-Ray Spectrographic Telescope (S054): Record spectra of solar flare X-ray emission in the 2 to 10 A wavelength range with a resolution of 0.5 A.

UV Scanning Polychromator Spectroheliometer (S055A): Photoelectrically record high resolution solar images in six spectral lines simultaneously.

Dual X-Ray Telescope (S056): Obtain high resolution (5 arc sec) photographs of the sun's coronal X-ray emission in the 3 to 60 A wavelength region.

Extreme UV Coronal Spectroheliograph (S082A): Obtain high resolution (5 arc sec) spectroheliograms of the solar atmosphere in the 150 to 650 A wavelength range.

Extreme UV Spectrograph (S052B): Record spectra of the solar disk in the 900 to 3900 A wavelength region with a 0.08 to 0.16 A spectral resolution.

Experiments Located in the Orbital Workshop

Specimen Mass Measurement (M074): Demonstrate the feasibility of mass measurement without gravity to assess food intake, urinary output, and bone and muscle changes during flight.

In-Flight Lower Body Negative Pressure (M092): Record heart rate, blood pressure, and electrocardiogram data during flight with negative pressure on the lower body to evaluate space flight cardiovascular deconditioning.

Vectorcardiogram (M093): Monitor electrical actions of the heart during space flight, using sensors and signal conditioners to obtain vectorcardiograms.

Human Vestibular Function (M131): Evaluate the condition of the crew during flight to determine angular acceleration comfort zone and to identify vestibular changes.

Time and Motion Study (M151): Use time and motion studies of standardized mechanical tasks to evaluate the relative consistency between ground-based and in-flight astronaut performance.

*Compiled by Martin Marietta Corp.

Metabolic Activity (M171): Evaluate man's metabolic effectiveness in space to determine long-duration mission requirements for logistics resupply, environmental control, and task planning.

Body Mass Measurement (M172): Validate a mass measurement device large enough to contain a man and to provide data for bone and tissue studies.

Gravity Substitute Workbench (M507): Access the use of aerodynamic and electrostatic force fields as an aid in the manipulation of loose objects in zero-g.

Astronaut EVA Hardware Evaluation (M508): Evaluate man's capability to perform work under the conditions imposed by space flight and develop quantitative design criteria applicable to future missions in space.

Astronaut Maneuvering Equipment (M509): Obtain data on the mechanical and human-factor problems encountered by man using maneuvering devices.

UV Stellar Astronomy (S019): Perform a partial sky survey of Milky Way star fields to obtain UV spectra using a Ritchey-Chretien objective-prism spectrograph.

X-Ray UV Solar Photography (S020): Obtain X-ray/UV solar spectra by a grazing incidence spectrograph to support development of solar flare prediction techniques.

Gegenschein Zodiacal Light (S073): Measure the intensity and polarization of the night sky light in the zodiacal and Gegenschein region.

Particle Collection (S149): Study flux, size, composition, and velocity of micrometeoroids in the near-earth environment.

In-Flight Aerosol Analysis (T003): Determine the aerosol particle concentration and size distribution in the spacecraft atmosphere as a function of time.

Crew/Vehicle Disturbances (T013): Measure the effects of crew motion on the dynamics of their spacecraft and determine how these motions affect high accuracy pointing experiments.

Foot-Controlled Maneuvering Unit (T020): Determine the feasibility of the maneuvering unit for astronaut translation and rotational maneuvers in space.

Coronograph Contamination Measurement (T025): Monitor the presence of particulate matter in the near vicinity of the spacecraft and provide measurements of the solar f-corona.

ATM Contamination Measurement (T027): Measure the sky brightness background caused by solar illumination of contamination particles around a spacecraft and determine the effect of contamination on the optical properties of lenses and mirrors.

Experiments Located in the Command and Service Module

Radiation in Spacecraft (D008): Measure and record the absorbed radiation inside the spacecraft to assure astronaut awareness of any dangerous increase in radiation levels.

Mineral Balance (M071): Precisely measure the input and output of calcium and nitrogen by the astronaut to quantify rates of gain or loss (also conducted in the OWS and upon return).

Effects of Zero-g on Human Cells (S015): Study the influence of zero-g on living human cells and determine if the absence of gravity has a significant effect on their metabolism.

Potato Respiration (S061): Determine whether removal from the earth's rhythmic geophysical environment will affect a well-known biorhythm.

Circadian Rhythm, Pocket Mice (S071): Determine the effects on the physical functions of pocket mice when removed from gravity and the geophysical 24-hour period.

Circadian Rhythm, Vinegar Gnat (S072): Determine the effects on the physical functions of vinegar gnats when removed from the gravity and the geophysical 24-hour period.

Experiments Located in the Multiple Docking Adapter

Zero-g Flammability (M479): Determine the effects of zero-g on the flammability of nonmetallic materials in a spacecraft environment.

Material Processing in Space (M512): Demonstrate and evaluate molten-metal flow characteristics under zero-g and space vacuum conditions.

Nuclear Emulsion (S009): Investigate the physical and chemical characteristics of primary cosmic radiation incident on the earth's atmosphere.

UV Airglow Horizon Photography (S063): Secure photographs of the UV emission from the airglow layers of the upper atmosphere.

Multispectral Photographic Facility (S190): Determine the extent to which multiband photography may be applied to earth sites using six Hasselblad electric cameras with synchronized shutters.

Infrared Spectrometer (S191): Manually acquire and track ground truth sites to obtain spectrometer data to evaluate earth resources sensing from orbital altitudes in the visible to infrared spectral regions.

Ten-Band Multispectral Scanner (S192): Secure quantitative radiance values simultaneously in ten spectral bands, from visible to infrared, using imagery scanning with automated data processing techniques.

Experiments Located in the Airlock Module

Expandable Airlock Technology (D021): Demonstrate the feasibility of employing expandable structures in an earth-orbital environment.

Thermal Control Coatings (D024): Determine the effects of the near-earth environment on thermal control coatings to gain new insight into the mechanisms of degradation.

Microwave Scatterometer, Altimeter, and Radiometer (S193): Obtain active and passive microwave data from space for application to earth resources disciplines.

Experiments Located in the Instrument Unit

Galactic X-Ray Mapping (S150): Perform a high sensitivity survey of a portion of the celestial sphere to determine galactic X-ray sources and to develop an understanding of the apparent phenomenon of X-ray background radiation.

Precision Optical Tracking (T018): Track the Saturn space vehicle with a laser radar system during the early launch phase to determine liftoff motions.

Preflight and Postflight Experiments

Bone Densitometry (M072): Make a densitometric comparison of preflight X-rays of selected bones of the body to evaluate bone demineralization under prolonged weightlessness.

Bioassay of Body Fluids (M073): Compare plasma and urine samples taken before and after flight to assess the metabolic changes in man as a result of space flight.

Lower Body Negative Pressure (M091): Apply negative pressure to the lower half of the astronaut's body before and after flight to ascertain the cardiovascular function changes resulting from space flight.

Cytogenetic Studies of Blood (M111): Determine the preflight and postflight chromosome aberration frequencies in the peripheral blood leukocytes of the crew.

Man's Immunity in Vitro Aspects (M112): Assay humoral and cellular immunity as reflected by the plasma concentrations of the major immunoglobulin classes, study the functions of blood lymphocytes, and assay selected coagulation factors.

Blood Volume and Red Cell Life Span (M113): Document changes in red cell mass, red cell survival, and plasma volumes occurring as a result of space flight.

Red Blood Cell Metabolism (M114): Determine the effects of space flight on red cell metabolism and membrane integrity.

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