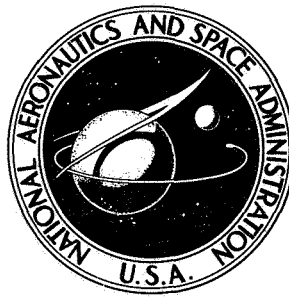


**NASA TECHNICAL NOTE**



**NASA TN D-8003**

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**FLIGHT PERFORMANCE OF SKYLAB ATTITUDE  
AND POINTING CONTROL SYSTEM**

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16. ABSTRACT  This note briefly reviews the Skylab attitude and pointing control system (APCS) requirements and the way in which they became altered during the prelaunch phase of development. The actual flight mission (including mission alterations during flight) is described. The serious hardware failures that occurred, beginning during ascent through the atmosphere, also are described. The APCS's ability to overcome these failures and meet mission changes are presented. The large around-the-clock support effort on the ground is discussed. Finally, salient design points and software flexibility that should afford pertinent experience for future spacecraft attitude and pointing control system designs are included.					
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## LIST OF ABBREVIATIONS

APCS	Attitude and Pointing Control System
ASCO	ATMDC Software Control Officer
ATM	Apollo Telescope Mount
ATMDC	ATM Digital Computer
ASS	Acquisition Sun Sensor
C&D	Control and Display
CMG	Control Moment Gyroscope
CMGIA	CMG Input Assembly
CSM	Command and Service Module
DAS/DCS	Digital Address System/Digital Command System
EPCS	Experiment Pointing Control System
EPEA	Experiment Pointing Electronic Assembly
EREP	Earth Resources Experiment Package
EVA	Extravehicular Activity
FOMR	Flight Operations Mission Room
FSS	Fine Sun Sensors
GNS	SWS Guidance, Navigation, and Control System Engineer
HOSC	Huntsville Operations Support Center
JSC	Johnson Space Center
LM	Lunar Module
MIB	Minimum Impulse Bit
MLU	Memory Load Unit
MOPS	Mission Operations Planning System (JSC)
MPC	Manual Pointing Controller

## LIST OF ABBREVIATIONS (Concluded)

OD	Operations Director
OMSF	Office of Manned Space Flight
OWS	Orbital Workshop
PCS	Pointing Control System
Rack	Canister Support Structure
RAPS	Real-Time Astrionics Problem Solving
RCS	Reaction Control System
RF	Radio Frequency
RG	Rate Gyro
RGP	Rate Gyro Package
RPM	Roll Position Mechanism
SI	Solar Inertial
STAC	Support Team for Attitude Control
TACS	Thruster Attitude Control System
TV	Television
UP/DN	Up/Down
WACS	Workshop Attitude Control System
WCIU	Workshop Computer Interface Unit
Z-LV	Z-Local Vertical

# FLIGHT PERFORMANCE OF SKYLAB ATTITUDE AND POINTING CONTROL SYSTEM

## I. INTRODUCTION

In 1967 a paper presented at the AIAA Guidance, Control, and Flight Dynamics Conference in Huntsville, Alabama, revealed for the first time the proposed Skylab attitude and pointing control system (APCS) [1]. The system requirements, Apollo Telescope Mount (ATM) configuration, control philosophy, and operational modes were presented and the APCS was described. The initial mission and system design requirements changed during the period of time before the Skylab was launched. This note reviews the initial and final APCS requirements and goals and their relationship [2-11]. The actual flight mission (and its alterations during the flight) and the APCS performance achieved is also presented.

Skylab was a tremendous success in furthering man's scientific knowledge, but perhaps Skylab will be remembered more for the anomalies and the efforts undertaken to solve them. On May 14, 1973, the unmanned Skylab orbital workshop was launched from Kennedy Space Center. Serious hardware failures began to occur during ascent through the atmosphere, and their spectre continued to haunt both the astronauts and the ground-based support team. However, these were not the only surprises affecting the design and operation of the APCS. Mission requirements for pointing to various stellar targets and to nadir for Earth resources experiments were added after the hardware was designed. The chance appearance of comet Kohoutek during the Skylab operational lifetime caused NASA to add comet observation to the mission requirements and to adjust the time when the third crew would man the Skylab. The development of new procedures and software for the opportunity to observe this visitor to our solar system is described.

## II. INITIAL DESIGN

The design of the Skylab APCS was based on evolving ground rules and directives for the ATM pointing control system (PCS) dating from June 1966. Prior to that time, various proposals and control moment gyroscope (CMG) systems had been studied. Ground rules set forth in response to directives from the Office of Manned Space Flight (OMSF) were included in a preliminary design review in July 1966. Three separate stages of development – the free flying ATM, the workshop attitude control system (WACS), and the wet workshop – characterized the initial design.

### A. Free Flying ATM

The PCS ground rules provided for a design using a command and service module (CSM) docked to a modified lunar module (LM) housing solar experiments, a 28-day maximum life, no redundancy, and a 1968 launch. The PCS design (1966) consisted of a fine and coarse



sun sensor, a single analog control computer with switching and logic, three double gimbaleed CMGs, CMG electronics and inverters, three rate gyroscopes, a hand controller, and analog meters. This system depended on the CSM reaction control system (RCS) for manual desaturation of CMG angular momentum and visual pointing of the experiments.

## **B. WACS Development**

The first major design impact occurred when the ATM vehicle was clustered with an S-IVB stage modified as the astronauts' living quarters.

The necessity for a major new operational capability, unmanned rendezvous and docking, and provision for attitude stabilization during the manned and storage periods prior to the ATM docking required the development of the WACS, for controlling the OWS, in addition to the PCS, for controlling the ATM. The WACS was to be activated following S-IVB stage passivation (removal of residual fuel, etc.). Astronaut commands or ground commands selected the WACS control modes and the necessary control phases. Following PCS activation the WACS would be placed in a minimum power consumption condition and could be re-energized as required. After the flight crew docked the CSM to the S-IVB stage, its RCS would be turned on to maneuver the cluster to the ATM acquisition attitude. Control of the cluster would then be assumed by the PCS.

## **C. Wet Workshop**

By June 1969, the WACS had evolved to a system consisting of rate gyros (RGs), discrete horizon sensors, conical scan horizon sensors and processing electronics, sun sensors, control computer, control switching assemblies, thrusters, and a control and display (C&D) panel. Redundant components and circuitry were provided to meet crew safety and mission success criteria [10].

## **D. Requirements**

The initial (1967) requirements (subsequently changed) are shown in Table 1 [1].

# **III. FINAL DESIGN**

## **A. Evolution of Final Design**

Clustering the ATM to the Orbital Workshop (OWS) imposed additional requirements on the PCS. Increased CMG momentum was required due to increased vehicle moments-of-inertia. To significantly reduce gravity gradient bias torques, the vehicle's principal axis of minimum moment-of-inertia had to be constrained to lie as closely as possible to the orbital plane while the ATM experiment package (canister) was pointed toward the Sun. Since this constrained the vehicle attitude about the line-of-sight to the Sun, a roll positioning

TABLE 1. APCS REQUIREMENTS<sup>a</sup>

	Initial APCS Requirement, X and Y, Z (arc sec)	CMG PCS, X and Y, Z (arc min)	Final Design	
			EPCS, X and Y, Z (arc sec)	Z-LV, X, Y, Z (deg)
Command Uncertainty	$\pm 2.5, 600$	$\pm 6, 10$	$\pm 2.5, 600$	$\pm 2.5$
Stability 15 min	$\pm 2.5, 450$	$\pm 9, 7.5$	$\pm 2.5, 450$	N/A
Jitter 1 s	$\pm 1, 60$	N/A	$\pm 1, 180$	$\pm 0.05$

a. See Figure 1

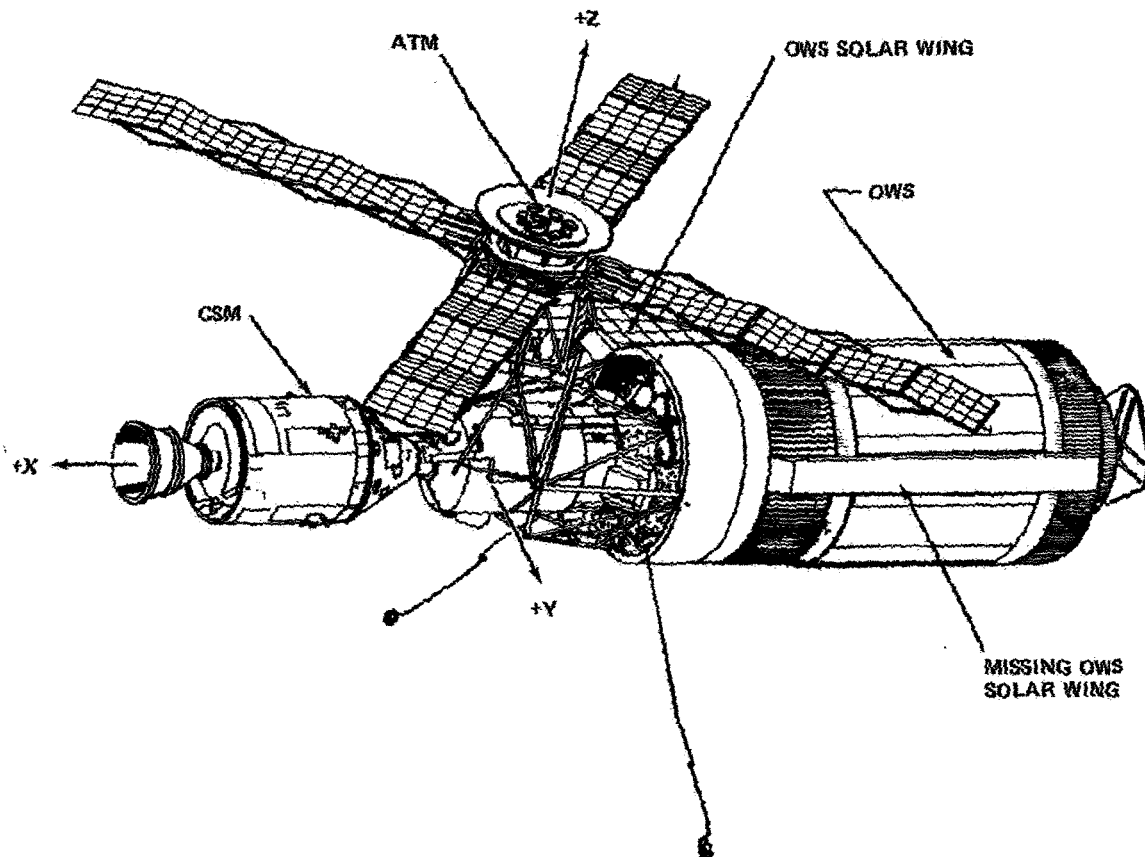


Figure 1. Skylab cluster.

capability of  $\pm 120$  deg was added to the canister. To preclude CMG saturation, the LM and CSM RCSs would be used to desaturate excess momentum. At the same time, experiment demands and crew motion combined to require a decoupled experiment package mounting with autonomous controls because it was realized that man-motion disturbances would tax the capability of the CMG system to maintain the experiment pointing stability requirements. This isolation between the canister and its mounting structure was provided by a 2 deg-of-freedom gimbal system using frictionless compensated flex-pivots. These were designed to allow  $\pm 2$  deg of rotation about the experiment pointing control system (EPCS) X- and Y-axis. Because these impacts, combined with increased readout needs and the addition of a star tracker reference, added to the complexity of the analog control computer, a separate electronics box, equivalent to a small digital computer, was proposed.

During the daylight portion of the orbit, the cluster X and Y attitude errors were sensed by the acquisition sun sensor (ASS). Differentiating the ASS outputs provided the necessary rate damping. During the night when the experiment pointing package was caged, the integrated canister RGs outputs were used to obtain attitude error information. Because of the canister roll capability, resolvers were provided to transform the gyro rates to the CMG control system coordinate system. X-axis attitude errors for the cluster were obtained by integrating the vehicle-mounted X-axis RG.

Attitude error signals for the EPCS were derived from the fine sun sensors (FSSs), and rate damping was provided by the canister-mounted RGs. The experiment package offset capability for each axis was developed by controlling the FSS optical wedges. An analog computer was used to implement the then-considered CMG H-vector control law, the CMG steering law, and the EPCS and CMG control error processing.

Reliability considerations for long-duration mission times caused designers to take a new look at redundancy. All mission-critical single-point failures were made redundant by introducing a switchover capability into the added duplex components. To accomplish this, additional rate gyros were added to the canister support structure (rack), obviating the need for the coordinate transformation resolver. Sensor averaging was implemented later. Extensive investigations showed that a digital (rather than analog) computer reduced the system complexity. To minimize the CSM and cluster fuel requirements, a CMG momentum desaturation scheme was instituted which utilized vehicle maneuvers against the gravitational field during the night portion of the orbit [8].

It was recognized that if the launch stack could accommodate the ATM, the program would be greatly simplified by eliminating extensive program and technical requirements. The capability to reduce program cost and complexity by eliminating the ATM as a free-flying module, the ability to rapidly activate the workshop by preinstallation and checkout prior to launch, and the capability to significantly expand the mission potential with the weight margins offered by a Saturn V launch vehicle supplied the rationale for conversion from a wet to a dry workshop.

The PCS and WACS were designed to operate autonomously during separate mission phases; however, the wet-to-dry conversion made it desirable to unite the two systems. This new system was renamed the APCS. Because of more ample weight margins the WACS was replaced by a simpler blowdown cold-gas thruster attitude control system (TACS).

The role of the digital computer was increased, and the ATM control computer was displaced. The CMG control law, error processing, and the bending mode filtering were to be performed in a digital fashion. The EPCS portion of the analog control computer was retained and assembled in a new unit called the experiment pointing electronic assembly (EPEA). The new mission requirements obviated the need for an LM; consequently, this module was eliminated.

The vehicle moments of inertia had increased almost 10-fold since the size of the CMG momentum had been selected and only an increase in momentum management sophistication prevented a need for a much earlier CMG momentum increase. The two-CMG operation had become extremely marginal (80 percent of the total momentum was needed for the accommodation of the cyclic torques alone; the remainder was incapable of handling the bias momentum accumulation and the maneuvers). Therefore, the CMG wheel speed was increased by 14 percent (this was the only possible way to increase momentum without a structural redesign), still leaving the CMG system somewhat marginal.

By 1971 the system requirements had been altered and had been divided into CMG PCS requirements and EPCS requirements (Table 1) [9]. Z-local vertical (Z-LV) requirements were added also. The requirements for the Z-LV mode of operation (e.g., during Earth resources experiments) are the same as those shown later in Table 2 except that a navigation error of  $\pm 2$  deg is acceptable.

## B. System Description

1. Introduction. The cluster and its associated control axes are shown in Figure 1. The APCS provides three-axis attitude stabilization and maneuvering capability for the vehicle throughout the mission and for pointing control of the Skylab experiment package.

To summarize, the APCS consisted of two separate control systems. The PCS provided the attitude stabilization and maneuvering capability for the vehicle. The EPCS provided pointing control of the ATM experiment canister and allowed offset pointing to targets of opportunity on the solar disk.

The major sections of the APCS, shown in Figure 2 are: ATM rate gyros, ATM ASS, star tracker, ATM digital computer (ATMDC) and workshop computer interface unit (WCIU), memory load unit (MLU), double-gimbaled CMGs, cold gas TACS, and the EPCS.

The following six control modes were addressable by C&D console switches and the digital address system/digital command system (DAS/DCS) for APCS operation:

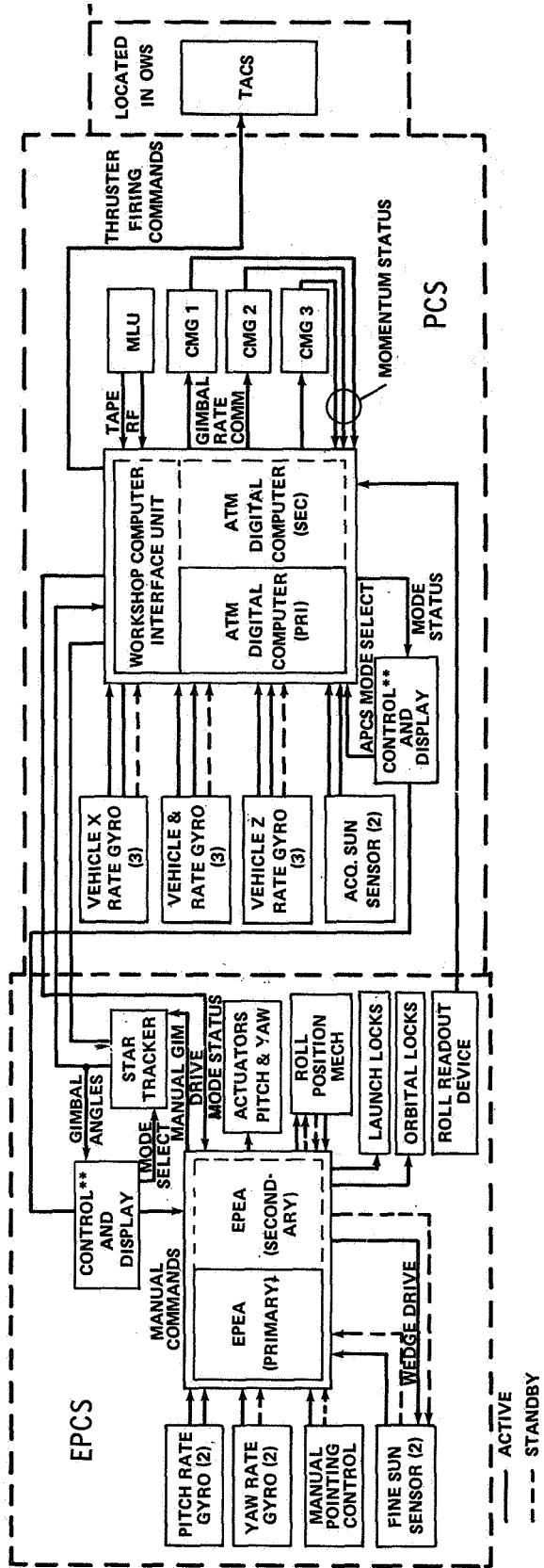


Figure 2. APCS block diagram.

1. Standby – This mode was used when no attitude control was required of the APCS. While in the standby mode, the CMG gimbal rate commands for attitude control were zeroed, and no firing commands were issued to the TACS.

2. Solar Inertial (SI) – This mode was used during experiment periods and for momentum dumping. The prevalent attitude during the daytime was with the cluster Z-axis pointing toward the Sun. Vehicle control was maintained through the CMG/TACS control systems.

3. Experiment Pointing – This mode was identical to the day portion of the SI mode with respect to vehicle control. In this mode, however, the EPCS was activated.

4. Attitude Hold/CMG – This mode required that the vehicle be held in an inertial attitude; all control torques were furnished by the CMG system utilizing TACS for necessary momentum desaturation.

5. Attitude Hold/TACS – This mode required that the vehicle be held inertially stable, with control torques furnished by the TACS.

6. Z-LV – This mode was designed to be used during the rendezvous phases of the mission or when Earth-pointing was required for experimentation periods. The Z-LV(R) attitude was defined as the -Z-axis pointing toward the Earth along the local vertical (nadir) with the X-axis in the orbital plane and opposite the velocity vector. The Z-LV(E) attitude was defined as the -Z control axis pointing toward the Earth along the local vertical (nadir) with the +X control axis in the orbital plane and pointing in the direction of the velocity vector.

2. PCS. The PCS was a digitally implemented combination CMG momentum exchange and reaction jet control system. The system was designed to operate in unison with the CMG system providing the primary control capability and with the TACS providing assistance if the CMGs momentarily were unable to control the vehicle. The TACS could also operate as the primary control system. Attitude error and rate sensing were provided by two ASSs and nine RGs (three per axis).

3. TACS. The TACS was composed of six cold gas thrusters and the necessary logic to select and fire the proper thruster. The TACS control law provided thruster firing commands to null out attitude and rate errors when control deadbands were exceeded.

The TACS was also used for CMG momentum desaturation as needed. Two thrusters provided uncoupled Y-axis control, and four thrusters provided coupled X- and Z-axis control. Two types of thruster firings were commanded, minimum impulse bit (MIB) and full-on firing

time. For full-on firings the selected thruster was fired continuously for at least 1 s. The MIB firming time was selectable from 40 to 400 ms to compensate for pressure decreases in the TACS cold gas supply tanks. At the beginning of the mission a thruster produced 440 N (100 lbf). This decreased to approximately 44N (10 lbf) at the end of the mission.

4. CMG Control System. The CMG system was composed of three orthogonally mounted, double-gimbaled CMGs with a stored momentum capability of approximately 3000 N·m·s (2200 ft-lb-s), as shown in Figure 3.

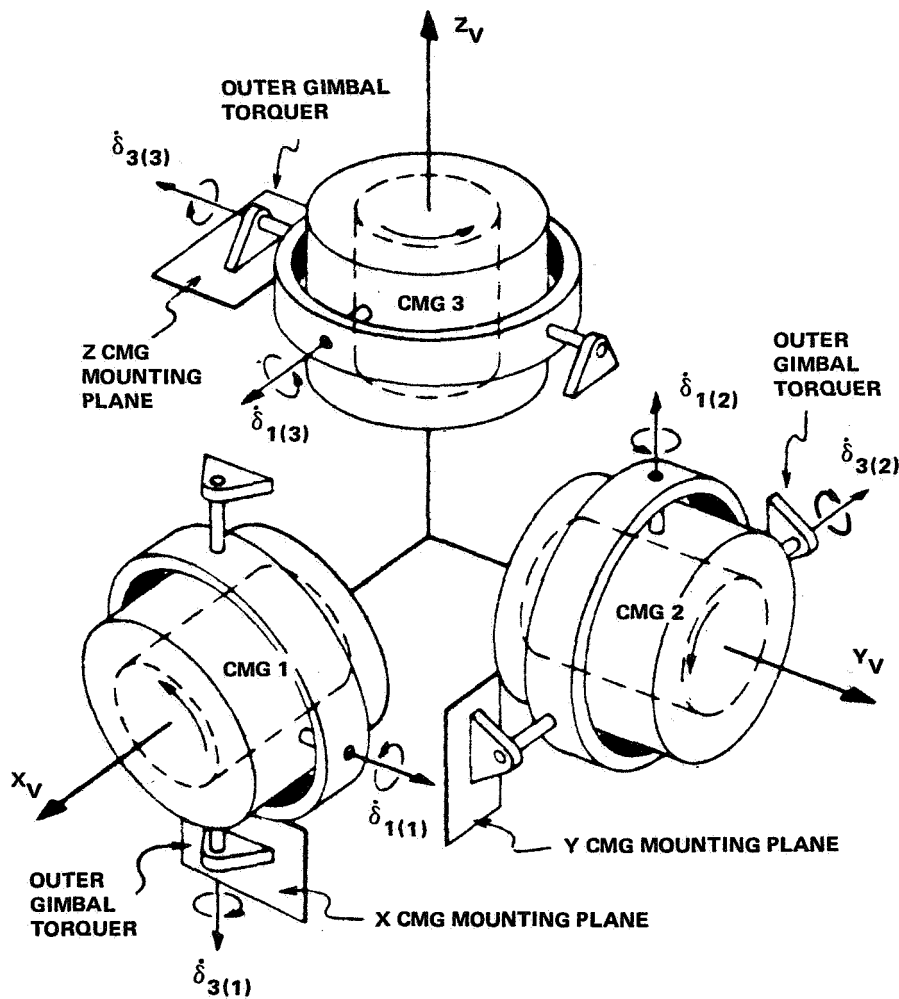


Figure 3. CMG orientations.

The CMG control law utilized three normalized torque commands and the CMG momentum status to generate proper CMG gimbal rate commands [5]. The control law consisted of three parts: the steering law, the rotation law, and a gimbal stop avoidance law. Other routines were included for specialized situations.

The steering law provided torques on the vehicle either for attitude maneuvers or to oppose torques from gravity gradient, vehicle vents, or crew disturbances. Gimbal rate commands were generated in such a way that the torques resulting on the vehicle were identical to the desired torques in direction and magnitude.

The rotation law attempted to minimize the probability of contact with the gimbal stops by reducing the largest gimbal angles. This was accomplished by rotation about the vector sums only. The total angular momentum was unaffected and no torque was exerted on the vehicle.

A gimbal angle reset routine was incorporated into the CMG control law to allow the CMG system to recover from undesirable gimbal angle positions and/or momentum configuration. It also permitted initialization to any desirable momentum state. The TACS eliminated the difference in momentum between the initial and final momenta.

Outer gimbal drive logic was provided during Z-LV maneuvers in order to force a desirable gimbal angle position. If it was sensed that a gimbal was moving in a direction opposite to the desired one, a momentary attitude perturbation was allowed and an open loop drive was executed to force the proper polarity.

5. PCS Operation. All control was delegated to the CMG system as long as it was capable of maintaining the error signal within  $\pm 20$  deg. If the error signal exceeded 20 deg, TACS ONLY control was initiated.

The Skylab used a four-parameter strapdown attitude navigation system consisting of RGs as inertial sensors and the ATMDC to calculate the strapdown algorithm. Two-axis sun sensors, a star tracker, and onboard analysis of the PCS response provided information to update the strapdown system. When an attitude error occurred, the CMG control law determined gimbal rate commands and the TACS control law determined the thruster firing commands. The CMG momentum status was monitored by the flight program through the CMG direction cosine resolvers.

A filter was incorporated in the CMG control law for each control axis. The purpose was to provide adequate stabilization and pointing of the rigid and flexible body dynamics. The control loop gains and filter coefficients were different for each axis.

Maneuvers were accomplished by two different schemes: attitude biases and strapdown computations. Attitude biasing was used for solar offset ( $\pm 4$  deg) and for momentum desaturation maneuvers and was accomplished by biasing the attitude error signal with the desired offset angle. The other maneuvers required maneuvering the vehicle to arbitrary time variant or inertial attitudes and were accomplished via strapdown commands. Large momentum changes in the CMG system were generally required to provide the desired maneuver rates.



6. Digital Implementation. Digital implementation was accomplished using an ATMDC and WCIU. The flight program was responsible for operating modes, Skylab attitude reference, navigation and timing, CMG control law, TACS control law, maneuvering, automatic redundancy management, function command, data display, telemetry, and experiment support. The ATMDC flight program was modular in design. Most attitude control functions were performed at the rate of five times per second, and the remaining functions were performed once per second.

7. CMG Momentum Management. Noncyclic disturbance torques would result in a net angular momentum buildup of the CMGs. Because of finite storage capacity of the CMGs, this momentum accumulation would eventually cause CMG saturation and loss of attitude control. To preclude this possibility and minimize the effects of noncyclic gravity gradient torques, the principal X-axis was maintained close to the orbital plane and momentum desaturation maneuvers were performed periodically during the night portion of the orbit [8]. The magnitude of the desaturation maneuvers was based on factors obtained by sampling normalized components of the total system (vehicle and CMGs) momentum four times during the day portion of the orbit.

8. Experiment Pointing Control System. The EPCS was used for pointing control of the ATM experiment package. It provided automatic stabilization of the experiment package about the X- and Y-axis. The FSS and RG sensors mounted on the canister supplied position and rate feedback to the EPEA. The EPEA contained the electronic functions to command the flex-pivot actuators, closing the control loop. The EPCS did not perform Z-axis stabilization.

Manual positioning about all three axes was provided for offset/roll pointing of the experiment package. X- and Y-axis offset pointing were achieved by means of a rotating optical wedge mechanism within the FSS. Offset commands could be issued from the manual pointing controller (MPC) or from the ATMDC. The roll position mechanism (RPM) was activated by command switches located on the C&D panel and on the ATM extravehicular activity (EVA) rotation control panel. All offset/roll commands were processed by the EPEA. A roll about line-of-sight capability was controlled by the ATMDC, utilizing the ATMDC wedge drive capability. The EPEA also provided an interface between the star tracker and MPC, for manual positioning of the star tracker gimbals. Other EPC and EPC-related functions were canister caging control, experiment alignment calibration, and experiment and FSS door control (see Figure 2).

9. Redundancy Management. All mission-critical single-point failures were eliminated. System redundancy was provided so that any component failure that could cause the mission to be aborted or preclude mission objectives was provided with a backup unit or an alternate subsystem configuration that could be selected without performance degradation. Hardware redundancy included the following items: nine RGs (three per axis), two ASSs (two channels per axis), three CMGs (two required for control), two ATMDC/WCIU units, two TACS thruster modules with quad-redundant solenoid valves, two FSSs (two channels per axis), two CMG input assemblies (CMGIAs), four canister RGs (two per axis), EPEA with five redundant channels individually selected, four canister torque motors (two per axis), and redundant power sources.

The redundancy management philosophy was that primary APCS mission critical systems, those related to system performance or crew safety, would be monitored and managed automatically, utilizing the flight program and backed by a manual switching capability. Capability existed to inhibit all or portions of the automatic redundancy program. The less critical systems were monitored manually by the astronauts using the C&D panel and by ground support using the telemetry link. Manual redundancy management switching capability existed via a switch selector and was commanded using the DAS/DCS. To ensure the integrity of the flight program, an ATMDC self-check capability was included.

To increase the probability of completing the Skylab mission, the MLU was developed to provide the means of loading the computer during flight. In addition to the regular 16k program, a skeleton 8k program capable of fitting either of the two 8k ATMDC memory modules located in each ATMDC was provided.

10. Strapdown and Maneuvers. Studies of the WACS showed that an all-attitude capability for the attitude navigation, maneuver, and control schemes was required. Long lead time hardware purchased for the ATM, such as Sun sensors and RG packages, could easily be adapted for use in a strapdown attitude navigation system. A software strapdown algorithm, employing quaternions used in mission analysis simulations, met the requirements of the Skylab mission because the algorithm used rate inputs and had no singularities. Quaternions were also used in software to calculate the maneuvers to be performed by Skylab.

## IV. OPERATION

### A. Mission and Performance Description

1. Planned Mission. The planned mission sequence was to place the unmanned Skylab, without the CSM, into a near-circular, 435 km orbit with a nominal inclination of 50 deg by a two-stage Saturn V launch vehicle. Within the 7.5 hr of the Saturn Instrument Unit lifetime, the ATM rack was to be oriented toward the sun, and the solar panels were to be deployed. The Skylab interior would then be pressurized to make it habitable for the crew. Approximately one day later the CSM, carrying a three-man crew, was to be placed into a temporary 150 by 222 km orbit by a Saturn IB launch vehicle. Using its own propulsion system, the CSM would achieve a rendezvous with Skylab and dock to an axial docking port. It was planned for the crew to remain on board Skylab for 28 days to conduct experiments. They then would prepare Skylab for orbital storage and return to Earth in the CSM. Two subsequent launches, similar to the second launch, were planned. Manned mission durations of no more than 56 days were anticipated. The first two flights were planned for the last quarter in 1972.

2. Actual Mission. When the flight mission was actually initiated on May 14, 1973, all did not go as planned. The micrometeoroid/thermal shield and one of two solar wings on the OWS were torn off during boost. The other workshop solar wing was deployed only 10 deg and generated no useful power. Fortunately the ATM and its associated solar wings were deployed and activated as planned. Skylab was in trouble, however, since it was able to generate only half of its designed electrical power and was without a thermal shield. To further complicate matters the immediate solutions to the thermal heating and electrical generation problems were contradictory. Electrically a sun incident angle of 90 deg was desired while thermally something less than 45 deg was preferred. This required a change in the Skylab nominal attitude, during its initial unmanned phase.

After the initial thermal problems were overcome, the basic mission was altered in three significant ways. First, observation of the comet Kohoutek demanded unplanned flexibility in the mission. Second, the scope and duration of Earth resources experiments were expanded. Third, the total mission duration was extended from the original three Skylab manned operational periods of 28-56-56 days to 28-60-85 days to take advantage of expanded mission requirements.

The performance of the APCS was well within the system design specifications as given in Table 1. In the first portion of the second manned mission, as the requirements for the observation of comet Kohoutek evolved, a special interest focused on how well the PCS could point the vehicle. To determine the pointing accuracy of the CMG control subsystem, a special test was conducted in orbit utilizing one of the experiment cameras. The results of the test are shown in Table 2 and are well within the design requirements.

TABLE 2. POINTING ACCURACY DATA

	X	Y	Z
Stability, arc min per 25 min	1.8	0.5	0.5
Jitter, arc min (worst case excursion)	± 0.6	± 0.45	± 0.5

The performance of the EPCS was also exceptional. Experimenters reported that resolutions of approximately 1 arc sec were attained on much of the solar imagery. The astronauts also reported that the system was extremely stable, as indicated by the absence of noticeable experiment cross hair motion when positioned on solar targets.

3. Mission Support Team. An MSFC mission support team for the APCS (STAC) was organized to provide real time support for Johnson Space Center (JSC). This support was to provide direction, answer questions, and analyze and solve problems that occurred. The team would receive problems or questions from the operations director (OD) in the Huntsville Operations Support Center (HOSC). STAC would then obtain answers from the proper support group or groups, coordinate the answers, and furnish a reply to the flight operations mission room (FOMR) through the OD at HOSC.

The original plan was to have two complete APCS teams. Each team consisted of a specialist in his field plus additional personnel to cover other contingencies. Each team was to be alternately on call for 24 hours. Because of the system and operational problems, the planned two teams had to be expanded to five teams to meet the continuous support required.

A prime factor in providing support for the APCS team was having adequate data. Six data sources were utilized by the team: real-time telemetry displays, digital television displays, limited viewing of JSC digital television formats, off-line telemetry tape processing by IBM, computer plots and tabulations from the Mission Operation Planning System (MOPS), and hard copies in the form of data books.

The APCS team was assigned a work room in HOSC. This room contained a TV monitor and communication lines to JSC, in addition to normal telephone communications. This room was too small to adequately house the APCS team so remote sites having various capabilities were utilized. IBM provided support in the areas of ATMDC software and hardware, data reduction, and maneuver simulations. Other system hardware was monitored and evaluated by the Real Time Astrionics Problem Solving Support Team. The Hardware Simulation Laboratory was used to verify flight programs and patches, develop procedures, examine hardware problems, and test some of the replacement hardware sent aloft with the second Skylab crew. Most of the simulations of maneuvers were performed on the Marshall Hybrid Simulation (EAI 8900). Support from Bendix Research Laboratories, Detroit, and Martin Marietta, Denver, was obtained in solving long range problems.

STAC spent several months practicing mission support. The first practices were used to acquaint the team personnel with communications, procedures, reference documents, and the coordination aspects of problems. Problems or contingency situations requiring solutions were used in the final practices. These practices involved the full team including various simulators to arrive at solutions to the problems.

## **B. Major Variations from Expected Operations [12 - 14]**

1. Thermal Attitude. On May 14, 1973, at 1730 GMT the unmanned Skylab Orbital Workshop was launched from Kennedy Space Center. Prelaunch tests and the countdown demonstration prior to the final countdown went very smoothly. At 63 seconds after lift-off, an unexpected telemetry indication of micrometeoroid/thermal shield deployment and separation of the solar array wing No. 2 beam firing was received. However, all other space vehicle systems appeared normal and the OWS was inserted into a near-circular Earth orbit of approximately 435 km altitude. The payload shroud was jettisoned and the ATM and its solar wings were deployed as planned during the first orbit. Deployment of the OWS solar wings and the micrometeoroid/thermal shield was unsuccessful. Evaluation of the available data indicated loss of the shield. Telemetry data also indicated that at about the time the solid rocket motors fired to decelerate the second stage, one of the solar wings was lost from the OWS. The remaining solar wing was released; however, there were indications that the wing was deployed only about 10 deg. An abnormal temperature rise in the OWS was observed and

attributed to the absence of the micrometeoroid/thermal shield. In the SI attitude, with the plane of the solar wings normal to the sun for maximum electric power generation, the OWS temperature finally exceeded its operating limit. In order to bring this temperature to within design limits, the OWS was rotated about the Y-axis by 45 deg from the sun 13 hours after launch to reduce the solar incidence angle and heat influx on the OWS. However, this attitude further reduced the power generation capability which had already been severely limited by the loss of the OWS solar array wing No. 2 and the failure of wing No. 1 to deploy. A continuing adjustment of attitude was necessary to keep the power and temperatures within acceptable limits. Temperatures and electrical measurements were used to update attitude strapdown computations since there was no ASS information in this attitude. Constraints to maintain adequate heat in other critical areas of the workshop and to optimize the operation of the APCS in an off-nominal mode added further complications. This delicate balance continued for approximately 10 days.

The electrical power available from the ATM solar wings (one-half of the total design capability) was decreased by the requirement to cycle certain power regulator modules on and off to prevent overheating caused by these unplanned vehicle attitudes. Although considerably below the total design capability of approximately 8500 watts, the power was sufficient for the critical vehicle loads. Many components and systems were turned off or were cycled as required to remain within the power generation capability. Maneuvering into and out of the various thermal control attitudes caused a much larger usage of TACS impulse than predicted. Sufficient propellant remained, however, for the three planned manned missions.

The launch of the first manned mission was delayed 10 days. In the 10-day period teams across the country accomplished the design, manufacture, test, and delivery to the launch site of four hardware systems intended to combat the temperature problem – an effort which under normal circumstances would have taken months at best. Three of the systems – one, a parasol to be deployed through a scientific airlock – were selected for flight and were stowed on board the CSM with other hardware for freeing the undeployed solar wing and replacements for the supplies expected to be affected by the abnormally high workshop temperature.

The first crew arrived at Skylab on May 25. Visual inspection from the CSM confirmed that the micrometeoroid/thermal shield and one of the OWS solar wings were missing. The astronauts also reported that the remaining solar wing was only partially deployed, seemingly held in that position by a metal strip from the shield. Television transmission enabled engineers on the ground to study the situation. After an unsuccessful attempt to free the solar wing, the crew docked and entered Skylab. They successfully deployed the parasol through the scientific airlock facing the sun and then activated the systems. With the parasol shading part of the area of the OWS and with the return to the normal SI attitude, the OWS temperature decreased over a period of several days from 55°C to 25°C (131°F to 77°F). The crew then established the OWS manning routine and for the next 11 days performed scientific and medical experiments under a reduced power profile. During a 3.5-hour EVA on mission day 13, the Commander and Science Pilot freed and deployed the partially extended OWS solar wing. Adequate power was then available, permitting a return to the original flight plan.

The return of systems to a powered-up mode and crew operations to near normal gave rise to hopes for an uneventful continuation of the mission. However, the early exposure of systems and components to attitudes and environments exceeding design limitations was to continue to plague the mission. The perseverance and ingenuity of dedicated mission control and supporting engineering personnel, together with the perseverance and dedication of the flight crews, would lead to the solution of each new and separate problem and would allow the Skylab mission to continue.

2. Rate Gyro Problems. Within the first 21-hours of APCS operation, failures of either telemetry measuring circuits or heater control circuits were evident on four rack RG packages (RGPs). Later in the mission, an additional rack RGP and one EPCS RGP showed identical symptoms. After detailed studies it was concluded that the six RGPs had experienced heater control failures causing them to overheat. All the hot RGPs showed much noisier outputs than the normal RGPs. Another problem noted with the hot RGPs was a change in scale factor. This caused redundancy management rate integral discomparers during maneuvers. It was possible to compensate in the ATMDC software for scale factor errors only in the Y-axis. Ultimately, through extensive analyses and test, the cause was proven to be a design deficiency. Use of a fiber washer, which took a permanent set when subjected to thermal cycling, allowed loosening of the power switching transistor mounting system, causing the transistor to thermally saturate and hold the RG heaters in the "on" position.

The second major RG problem was a drift anomaly. Excessive RGP drift rates first became evident shortly after switchover to ATMDC control. Drift rates as high as 18 deg/hr were noted. The high drift rates made it difficult to maintain the correct attitude for thermal control during the first 10 days. Constant drift rates could be compensated for by ground command to the ATMDC. However, the drift rates changed suddenly and caused difficulty until the new rates could be measured and compensated for. As time passed in the mission, the magnitude of the drift rate changes decreased. Eventually, at least one RGP in each axis became stable and was used through the remainder of the mission. After considerable investigation it was established that the high drift rates were caused by gas bubbles in the RG flotation fluid. A design deficiency exposed the float chamber bellows to the hard vacuum of space, releasing entrapped gases present in the flotation fluid. The decrease in drift rates as the mission progressed was attributed to either reabsorption of the gas by the flotation fluid or relocation of the bubbles in the float chamber due to float fluid agitation.

As the mission progressed, degradation was seen in the operation of some of the hot RGs. Two of the Y-axis RGs had shown full scale oscillation, and a Z-axis RG had failed hard over. Additionally another Z- and X-axis RG would also act up occasionally. By the time the first crew returned, the seriousness of the problem had become apparent. The loss of another Y-axis RG would have meant the end of Skylab and the other axes did not look much better. More RGs were needed, but the existing ones could not be replaced because of their inaccessibility (within the ATM rack). It was decided that an orthogonal platform with six RGs (two in each axis) would be packaged together (termed a six-pack) and then mounted interior

to the Skylab in close alignment to the original rack RGs. The package was carried up by the second crew and was connected to the system during an EVA. Mating of four electrical connectors was required, one of which was critical. Failure to reconnect this connector would most likely have meant mission termination since all RGP signals fed into the ATMDC through this connector. During the installation time, no attitude control was possible, and the vehicle was permitted to drift. No problems were encountered. The six-pack RGs were powered by a single power source. To avoid an undetectable single point failure, one RG of the six-pack in each axis was paired with the best original rack RG. The operation of the six-pack RGs after installation was excellent, and there were no more significant RG problems for the remainder of the mission.

3. CMG Anomalies and Failures. No redundancy of the CMG wheel speed measurement was provided, since the speed indication was for display only. Twelve days after launch the indicated wheel speed of CMG No. 3 went from nominal to zero within 1 s. The spin motor currents and the bearing temperatures remained nominal. This indicated a failure of the speed sensor; this was supported by the fact that the APCS continued to perform normally. Later in the mission there also were several erratic indications in the speed measurement of CMG No. 2 which appeared to be self-correcting. The CMGs operated normally until the ninth day into the third manned mission when, upon site acquisition, telemetry indicated zero wheel speed and a significantly overheated spin bearing on CMG No. 1. The spin motor currents were about twice normal, and the RGs mounted in the vicinity of the CMGs were very noisy, but the bearing temperature was decreasing. None of the CMG automatic shut-down levels had been reached. There was no loss of attitude control, and the ATMDC was in normal three-CMG control. After several minutes of analysis the mission control team declared that CMG No. 1 had failed and commanded that the electric brake be applied. This cut the power to the CMG and forced the ATMDC to reconfigure to two-CMG operation. Subsequent evaluation of the data showed that the difficulty started with the beginning of the second momentum desaturation maneuver. The maneuvers, however, were relatively small and had been successfully completed by the time telemetry was reacquired.

The probable cause for CMG No. 1 failure was lubrication starvation of one of the spin bearings. However, it was difficult to reconstruct the events just before the failure, since full telemetry was available only when the vehicle was over a ground station. Momentum indications were that the wheel had spun down within an hour, which was very fast when compared with the braked spindown time of about 5.5 hr and the coast-down time of over 15 hr. Further investigation revealed that the spin bearing had been in distress on four occasions before the final failure. The distresses seemed to be linked to low bearing temperature (before the heater came on) and to high gimbal rate demands (for maneuvering). They were characterized by above nominal wheel spin motor currents, an abnormal bearing temperature, and a drop in wheel speed. The bearing distresses before final failure had been ignored since their significance was not recognized. Because another CMG failure would have severely curtailed the mission, everyone concerned was very sensitive to bearing distresses on the two remaining CMGs. CMG No. 3 did not show any distresses, but one spin bearing of CMG No. 2

showed an ever increasing number, coupled with an increase in severity. It was obviously only a matter of time before CMG No. 2 would also fail. Relief was attempted by cancelling large maneuvers when CMG No. 2 was in distress, by reducing the maximum possible gimbal rate during the desaturation maneuvers from 4 deg/s to 2 deg/s (via a patch in the ATDMC), and by manually managing the bearing heater operation to avoid low bearing temperatures. While it cannot be proven, it is still felt that these measures prolonged the life of CMG No. 2 until the end of the mission.

4. Star Tracker Operation and Failure. A gimballed star tracker was used to provide experimenters with knowledge of vehicle roll attitude about the sunline to within 10 arc min. For the first manned mission, the normal operating plan was to provide continuous roll reference information from the star tracker except for occultation periods. Frequently a particle of contamination came into the field-of-view, and the tracker began tracking the particle. This destroyed the experimenters' knowledge of roll reference, and the crew had to drop what they were doing to reposition the star tracker gimbals to reacquire the star. Contamination tracking could have been avoided by a gimbal angle reasonableness test.

A different operating procedure was used during the second mission to minimize the problem of contamination. Normally the tracker was placed in a standby configuration, and periodically the crew would operate the tracker until the star was acquired and the computer had received the gimbal information. Then the tracker was switched back to standby. The tracker worked well with this procedure except for five occasions when the shutter stuck in the open position. On each occasion the shutter would recover, usually within several hours. Realizing the possibility of detector degradation after the first shutter failure, the crew was asked to position the tracker to look at a dark surface of the vehicle when the shutter was failed in the open position. Unfortunately, the tracker had been degraded by 30 percent to 50 percent (probably by Earth albedo) when the shutter had first failed in the open position. One of the consequences of this periodic star tracker operation was that the software which provided canister roll reference calculations and telemetry did not have the accuracy required by the experimenters. A software patch to provide better calculations of roll reference was implemented for the third manned mission. An extensive data reduction process was initiated to recover more accurate roll reference information prior to the patch.

The tracker suffered catastrophic failure 42 days into the third manned mission. The outer gimbal position indicator suddenly went to zero. Analysis indicated that the optical encoder had failed. As a backup, periodic sextant star sightings were obtained from the CSM to update the roll reference. This procedure was time consuming but the improved performance of the strapdown system operating with the six-pack RGs allowed the system to operate without updating for long periods of time.

5. Astronaut Suit Vent. No special treatment was originally planned for the EVA activities as far as the APCS was concerned. The hatch vent torque would be absorbed by the CMGs and the momentum desaturation scheme would dump the accumulated momentum



during the next orbital night. However, the so-called nonpropulsive astronaut suit vent had been covered by a flap to avoid contamination of the ATM instruments during EVA. As a consequence relatively large disturbance torques were experienced — large enough to saturate the CMG momentum and cause TACS firings as well as gimbal stop problems during momentum desaturation maneuvers. This resulted in the activation of the CMG gimbal reset with more TACS firings. Since the astronaut orientation during the EVA was not predictable and since the gimbal reset (which used much TACS fuel) was always possible, it was better to inhibit momentum desaturation with CMGs and desaturate with TACS directly. This was the policy until the failure of CMG No. 1, which aggravated the stop problems. For two-CMG operation the CMGs were subsequently electrically caged to the nominal momentum profile during EVA, thereby absorbing most of the gravity gradient torques. The TACS was put in control to maintain the vehicle within its attitude deadband. Although this method always cost TACS fuel, it avoided the penalty of higher TACS cost that would result from loss of CMG attitude control with attendant automatic switchover to TACS control.

6. Experiment Maneuvers. In the 50 days between the second and third manned missions, Skylab systems were analyzed to determine the best way to take advantage of the appearance of a comet (Kohoutek) which would pass close to the Sun on December 27. A decision was made to slip the launch of the last crew 3 weeks so that comet perihelion would occur midway into the manned mission. The comet was to be photographed (by cameras mounted in the OWS) during its approach to and departure from our solar system. This photography required maneuvers to bring the comet within range of an articulated mirror system used with the cameras. The mirror had to be shaded from the Sun so that stray light would not enter the camera. To do this, computations were performed on the ground to maneuver the vehicle so that one of the ATM solar wings shaded the mirror. At the same time, the X principal axis had to remain in the orbital plane to prevent a buildup of momentum. When the comet approached the sun to within an angle of approximately 5 deg, the sensitive ATM experiments were used to obtain analysis of the comet structure in various wavelengths. To provide for these new maneuver requirements, the digital computer was reprogramed to reduce the size of the smallest attitude bias command from 0.1 deg to 0.01 deg. The largest allowable SI attitude bias was also increased from 4.00 deg to 5.25 deg to increase the opportunity to use the Sun as an attitude reference while pointing the ATM to the comet.

Many other types of maneuvers were performed by Skylab for gathering scientific data. Earth resources maneuvers were required to point the experiments to the Earth. These same experiments required periodic calibration by slewing them across the Moon. ATM experiments were pointed, in an open loop fashion, to several different celestial objects using the strapdown system as an inertial reference. There were 60 Earth resources maneuvers planned, 94 were performed; 3 rendezvous maneuvers were planned, none were performed; no comet maneuvers were planned, 59 were performed; and no celestial object maneuvers were planned, 4 were performed.

7. ATMDC Patches. Prior to Skylab launch a number of contingency situations were identified and 24 software patches were developed as solutions. Some of these patches were used to solve problems as they arose. Fourteen were implemented during the Skylab mission.

The ability to modify or patch the existing flight program proved to be mission-essential. This capability also made it possible to support the new program objectives related to comet Kohoutek.

8. Crew Motion. Early in the first manned mission, the mission support group became concerned about wild motions on RG telemetry, as shown in Figure 4. When the crew was asked what they were doing, they said they were jogging. By running around the walls on the circumference of Skylab, similar to a squirrel in a revolving cage, the three astronauts were able to maintain upright positions. This exercise on the part of the crew was the most violent crew motion disturbance experienced by the APCS. As a consequence this type of exercise was prohibited thereafter. Figure 4 also shows more routine levels of crew motion during crew sleep and wake periods. In all cases the EPCS maintained acceptable solar pointing. With normal levels of crew motion disturbance the crewmen estimated that the EPCS jitter was less than 1 arc sec. Further, experimenters have been very pleased with the quality of photographs taken of the Sun.

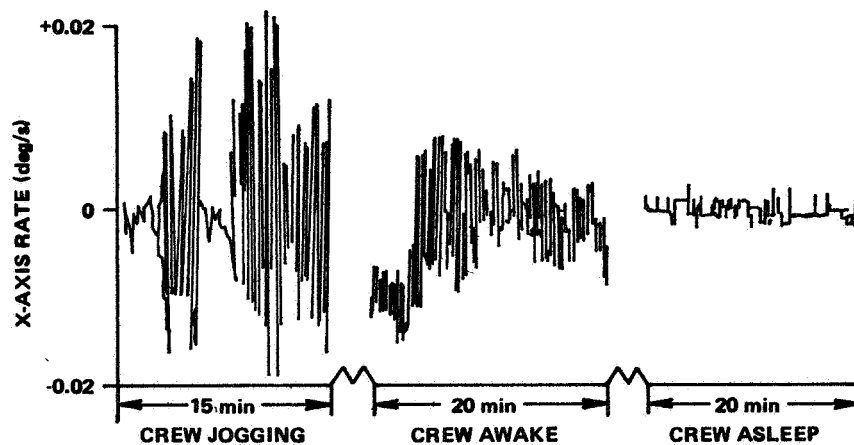


Figure 4. Jitter caused by crew motion.

9. EPC-Derived Rate Control Assembly. Following the loss of the EPC primary up/down (UP/DN) RG and in view of the overall problems experienced with the Skylab RG processors, it was felt that there was a significant possibility that the secondary UP/DN RG would fail. The EPC was equipped with two RGs per axis, so a second UP/DN RG failure would have terminated use of the EPC. Replacing or supplementing the EPC RG system, such as had been done in the CMG/TACS system, was not considered feasible. Subsequently, a device called the EPC derived rate control assembly was designed. It was to be inserted in series with the FSS output for the purpose of producing a pseudo-rate signal to stabilize the EPC system in lieu of using signals from the canister RGs. The device was never installed, however, because no further EPC RG failures occurred.

10. Post Mission Tests. After completion of the last manned mission, CMG No. 1 (which had failed earlier in the mission) was turned on to see if it would run. Power was applied to the wheel for 8.5 hr. From the currents it was concluded that the spin motor torque of about 0.13 N·m (about 18 in.-oz) did not overcome the bearing friction and the wheel did not turn.

End-of-mission testing was also conducted on CMG No. 2. During spin-down the bearing torque was calculated to be 0.034 N·m (4.8 in.-oz) which, while greater than nominal, is within the range of torque for normal bearings. This indicated that little permanent damage had been incurred by the bearings. It was felt that the results of this test supported the theory that the problems observed were due to retainer ring instability because of insufficient lubricant in the bearing raceways and the retainer ring.

After the final crew had departed and the control system was deactivated, a 16k program was loaded successfully from the tape in the MLU tape recorder. After a short interval to verify that the program was functioning, a 16k program was loaded successfully from the ground. This marked the first time an in-flight computer had been loaded in total from the ground by RF uplink.

On February 8, 1974, the Skylab vehicle was maneuvered to its storage attitude. In this attitude the +X principal axis lies along the gravity gradient vector in a direction away from the Earth with the +Z principal axis lying along the vehicle's negative velocity vector. Ground tracking indications are that the vehicle is stable in this attitude.

### C. Improvements/Lessons Learned

1. CMG Rotation Law. The CMG rotation law operated as desired for three CMGs with the docked (manned) configuration. A modification to the rotation law giving the largest gimbal angle the proper weight, while still allowing a compromise between it and the next smaller gimbal angle, would have been preferable to the linear addition used [5]. The stop problem could have been softened if the freedom of the outer gimbal stop could have been increased from 350 deg (stop to stop) to at least 450 deg. This change had been requested, but development of the long lead time hardware items was too far advanced to implement the change. Of course the very best solution is the complete elimination of at least the outer gimbal stop (the inner is of much smaller importance). On Skylab the analysis of the stop problem cost an immense amount of manpower, computer time, and at least 2 years of development effort. Without stops the ATMDC memory requirements for the implementation of the CMG control laws could have been cut considerably by elimination of the rotation law and the outer gimbal drive logic and by simplification of the gimbal reset routine.

2. Attitude Error Limiting. The maximum CMG momentum envelope is a sphere. This matches well the attitude error generation method using quaternions, which treats all directions in space equally. The CMG torque command is limited only in magnitude by

proportionally scaling the components. This philosophy was not followed in determining the limits on the attitude errors. Because the control gain about the X-axis was seven times smaller than about the Y- and Z-axis, there was a significant difference in the attitude error limits. As a consequence the torque command vector direction changed drastically when a limit was reached. Any time the X-momentum was larger than about 1220 N·m·s (900 ft·lb·s), the CMGs were saturated, and all attitude errors were on their limits, the additional momentum then would be drawn out of the X-axis which, due to its small inertia, resulted in a relatively large X vehicle rate and a large attitude excursion. These forced a switchover to the TACS-only mode with the associated large TACS fuel consumption (due to relatively high vehicle rates enforced by the TACS logic when reducing the attitude error to zero). The hard attitude error limiting precluded the large X attitude error having any effect. A proportional limit on the attitude error would have eliminated the problem. Two conditions were required for the problem to manifest itself. Momentum desaturation maneuvers (the regular maneuver scheme used rates only) had to be in progress, and the momentum prediction inherent in the desaturation scheme had to be wrong. This happened once because of an RG integral test failure and once because of excessive and varying astronaut suit vents during EVA. The problem was minimized by carefully managing the system, such as by inhibiting the momentum desaturation during later EVAs.

3. Finer Resolution of Attitude Error. Jitter amplitude is a function of the quantization of the attitude error. When the APCS was in the SI mode, the full precision of the strapdown algorithm was applied to the attitude error. In the attitude hold mode, the attitude error was calculated by quaternion multiplication. The multiplication was done in single precision which limited the resolution to 25 arc sec, whereas the resolution of the attitude error from the strapdown algorithm was about 0.1 arc sec. Figure 5 shows a comparison of the jitter obtained from the attitude hold and SI modes.

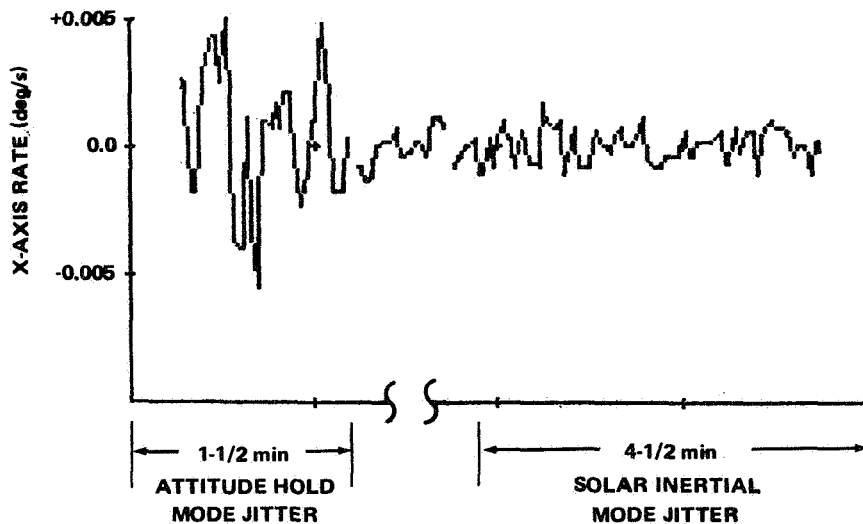


Figure 5. Attitude error jitter.

To improve the jitter during the comet and X-ray star maneuvers, a special procedure was used to make the computer use the SI mode logic while pointing at the target. This was accomplished by initializing the strapdown after maneuvering to the target and then selecting the SI mode with the sun sensor powered down. This allowed the target to be observed with the best jitter available while preventing the sun sensor from slewing the vehicle back to the sun.

4. Control Computer to Handle More Hardware Functions. While the ATMDC was used to monitor and test many hardware components in the Skylab operation, this function should be expanded in future space vehicles. A digital computer could also aid greatly in complex experiment setup procedures which would free astronauts for the more important functions of data gathering and interpretation. Skylab demonstrated the need for flexibility in program alteration for large digital control computers. A lesson learned from the Skylab mission was that having fully digital control systems for spacecraft is an attractive design concept.

5. Integral Control Law. A large part of the pointing error observed during the stellar X-ray pointing experiment and the comet Kohoutek pointing could have been eliminated by using an integral control law. The gravity gradient torques cause a pointing error and this error can be nulled by an integral control law. Such a law was developed and a flight computer patch was designed. The software failed to provide the predicted improvement during ground verification so it was not implemented. Nonoptimum scaling of the fixed point calculations was probably the reason for the failure.

6. Design Requirements and the Actual Mission. Design requirements and guidelines are obviously necessary, but the Skylab mission showed these should be considered to be the minimum design. If at all possible more capability or flexibility should be designed into the systems. The following examples will illustrate the point.

Including docking failures and two-CMG operation, the predicted TACS impulse usage was 160 kN·s (36 000 lb-s) for the life of the Skylab. The vehicle was loaded at launch with about 375 kN·s (84 000 lb-s) or 235 percent of the predicted ("design") usage. This was fortunate since 190 kN·s (43 000 lb-s) or about 120 percent of the predicted usage was used during the first 2 weeks in maintaining the thermal attitude. In this attitude the momentum desaturation scheme could not work and desaturation had to be made via the CMG gimbal reset with the associated high impulse usage. This usage would have been even higher had the ground support team not been able to develop a backup method to keep the X-principal axis close to the orbital plane. A large portion of the TACS fuel used during the mission can be identified as having been used under anomalous operation conditions. However, the TACS usage during nominal operation is consistent with preflight predictions. TACS usage during EVAs proved to be higher than expected as a consequence of the astronaut suit vents.

During the last manned mission, TACS expenditures rose following the CMG No. 1 failure. Decreased CMG momentum capability coupled with increased maneuver requirements, especially for comet Kohoutek observation, placed an added burden on the TACS budget.

Mission planners had to minimize TACS usage while allowing full experiment operation. The most significant conservation technique proved to be the orbital noon-to-noon earth resources experiments (EREP) pass.

Pointing the ATM at targets other than the Sun was never specified; but, since it was feasible with the onboard maneuvering scheme, ATM was not only pointed at comet Kohoutek but also at Mercury (to verify comet Kohoutek pointing capability) at various stellar X-ray sources. Special maneuvers to point the EREP package at the Moon for calibration were also made. This off-solar pointing required new computer programs on the ground to generate the maneuver angles to point at the target while keeping the X-principal axis in the orbital plane when required to minimize momentum accumulation.

The momentum desaturation scheme used the orbital plane angle (the angle about the sun line by which the vehicle X-axis was rotated out of the orbital plane) for the desaturation maneuver calculations. The star tracker, when active, supplied this angle. When not active, its last output was utilized for the six subsequent orbits, adjusted by the changes the desaturation scheme commanded about the sun line. This method assumed that the star tracker was locked onto a star and that the RG drift was nominal. When the star tracker was inactive for long periods, the desaturation scheme used a calculated orbital plane angle based on the estimated inertia properties of the vehicle. As it turned out the star tracker tracked contamination particles several times during the mission. During tracking of particles the indicated orbital plane angle error often was quite large, but the desaturation scheme was flexible enough that the performance degraded only when the error exceeded 10 deg. The assumption of reasonable RG drift was severely violated until the installation of the six-pack RGP by the second crew. The programmed inertial parameters, the direction of the principal axes, and the calculation of the orbital plane angle were in error due to the loss of the micrometeoroid/thermal shield and one solar wing. In spite of this, the desaturation scheme worked well. The errors were eventually corrected by patching the ATMD software.

The attitude control law and CMG control law combination could accommodate a large deviation of the actual CMG momentum magnitude while assuming that it was at its nominal value. This was demonstrated when attitude control was not impaired when CMG No. 1 failed. Control system performance appeared normal, and the ATMD redundancy management had not realized that anything was wrong. Therefore, action from the ground had to initiate two-CMG operation.

The switchover was very smooth without any attitude disturbance (a large maneuver with a failed CMG would have shown that something was wrong, but only small desaturation maneuvers were in progress at the time).

7. APCS Simulations. Many simulations (about 20) were used in the APCS design and development. Due to the planned length of the mission, it was not feasible to simulate the entire mission. Therefore the various simulations verified concepts and software at the normal

and extreme values. In addition, contingencies such as two-CMG operation were studied extensively. The speed range of these simulations varied from real time to 100X real time depending on the speed of the computer and the complexity of the models. In general, those simulations concentrating on dynamic response utilized models with greater hardware detail and operated more slowly but did not require as long an examination period. The most complex and demanding areas to be simulated were those of TACS budgeting, momentum management, and maneuvering. The types of parameters that were varied included solar elevation, CMG configuration, and maneuver profiles. These studies had to be repeated many times in the development history, as simulations were updated to reflect changes in control concepts. After the momentum management laws had been finalized, computer outputs showing expected maneuver profiles were generated.

While all simulations were very useful for the APCS development, only a very few proved useful for real-time mission support. One such simulation was the fast MSFC hybrid which was located in the same building as the HOSC. Its maximum capability of 100X real time made it useful for mission support and as a backup to the momentum management program of the MOPS. It was available 24 hours a day and was used regularly to optimize the daily flight plan in order to minimize TACS usage and avoid gimbal stop problems during maneuvers. The studies became even more critical after the failure of CMG No. 1 and the resulting switch to two-CMG control where there was practically no momentum margin. [15, 16]

8. Easier In-Orbit Maintenance. Certainly one of the lessons learned from Skylab was that a highly motivated crew can do a tremendous amount of in-orbit troubleshooting, maintenance, and repair, i.e., thermal shield deployment, freeing the SWS solar wing, six-pack RG installation, etc. Even more could have been done if the Skylab had been specifically designed with an in-orbit maintenance capability. Future spacecraft designers should keep this in mind, especially for vehicles that will be in space for long periods of time.

9. Nomenclature and Coordinate Systems. Nomenclature and coordinate system definitions usually do not receive the proper attention very early in the definition phases of a program; this leads to unnecessary complications. The Skylab program was no exception. Early in the program the attitude control people noted that due to a lack in coordination the structures people had mounted the CMGs quite differently from what was intended. The structural designation was retained; this required the modification and reprogramming of several very involved hybrid and digital simulations. Rather awkward nomenclature had to be carried all the way through the mission since a simplification was not attempted early enough. The CMG gimbal angles had a subscript with four characters rather than the minimum of one. Two definitions of the solar elevation angle ( $\eta_x = -\beta$ ) were carried throughout the mission. One originated from a mathematically positive definition, the other from previous usage. The mass property coordinate system was rotated 180 deg from the guidance and control coordinate system, and all mass and inertia data had to be translated.

The pitch, yaw, and roll nomenclature, while well defined for ships and craft, leads to much confusion when it is applied to a space vehicle like Skylab. Skylab consists of different parts, each with its own logical definition of pitch, yaw, and roll. For example, the X-axis

is roll for the OWS and the CSM, but the Z-axis is roll for the ATM experiment canister. Such nomenclature and definition problems should be avoided in future programs.

10. Improved Ability to Measure Misalignments. Uncertainties in caging the EPCS were the probable causes of the failure to detect X-ray stars during the galactic X-ray experiment. Skylab was maneuvered to point the solar experiments to an X-ray star with the EPC system caged. In some instances the star tracker was used to detect errors in X-ray star pointing by making two other star sightings. The crew would take two other star sightings with the star tracker to determine where the experiments were pointed. Small bias maneuvers were then performed to reduce this error. Unfortunately, any play in the EPC caging mechanism caused a misalignment that went undetected by the star tracker because it was mounted on the vehicle. In one instance, the X-ray star also emitted visible light. One of the experiments, a white light (solar) coronagraph with a crew TV display, was used to observe the star location. Bias maneuvers were then made to point the star to the center of the field of view of the coronagraph. Because the coronagraph had an occulting disc in the center of its field of view, navigation errors had to be measured in the visible doughnut-shaped area. This scheme depended on the TV system being linear to within 1 or 2 percent. In postflight debriefing, the crew reported that the linearity was poor; this is the probable cause of failure to obtain data on the visible X-ray star. A lot of ground analysis and crew time was spent on this experiment. The inclusion of a fixed head star tracker would have allowed the EPCS loop to be closed around a star tracker, then the accuracy and stability required for the X-ray experiment could have been readily achieved.

11. Ground Testing. The extent of the drift problem in the RG was not apparent from the tests performed. RG processor drift was not measured in vacuum until thermal vacuum tests were performed on the assembled ATM. Telemetry was used to monitor RG processor outputs, and a special preflight ATMD program provided a gross check. The telemetry system had some noise, and the seismic vibration levels in the thermal vacuum chamber caused the RG outputs to be extremely noisy. Since the ground support equipment was programmed to monitor the RGs by comparing the outputs of the three RGs on each axis, the test had to be insensitive to drift because of the high noise levels. The preflight ATMD program used a similar method to monitor the RGs. With this level of processing, two RGs were found to be drifting excessively and were replaced. The full extent of the RG drift probably could have been determined if the preflight program compared the integrals of the RG outputs, like the flight program, instead of comparing raw rates. The tests could have been made much more sensitive and perhaps the extremely erratic nature of the drift problem could have been determined.

12. Attitude Determination. A lot of ground support effort could have been saved if solar aspects sensors had been provided, since the thermal attitude required operation for several days without an attitude reference update from the sun sensor. Other means of determining attitude with respect to the sun had to be found. A method of determining solar aspect by analyzing the OWS solar wing currents was perfected prior to the flight. However, one wing was lost during boost and the other could not be deployed. Experts from the power



and thermal areas were consulted and within hours several other backup attitude determination schemes were developed. Analysis of the outputs of the functional ATM solar wings provided a measure of the solar aspect cone angle to an accuracy of about 1 deg and the sun could be maintained in the vehicle X-Z plane by observing the output of the temperature transducers. This method was used for updating the strapdown reference system to account for the RG drifts during the major portion of the thermal attitude period.

Another scheme for measuring cone angle was developed using a quartz crystal contamination monitoring instrument. This method was not as accurate as the scheme using the solar wings. A method was finally developed which determined vehicle attitude from the CMG momentum samples. This scheme could determine vehicle attitude with respect to the Earth in three axes and showed the most promise for emergency attitude determination. The momentum scheme was not available until the end of the thermal attitude period so it found little application until the star tracker failure occurred in the third manned mission.

## V. CONCLUSIONS

Skylab was the first manned spacecraft to utilize large CMGs for momentum storage and attitude control, the first to utilize vehicle maneuvers for CMG momentum desaturation, the first to utilize a fully digital control system with in-orbit reprogramming capability and extensive automatic redundancy management, and the first to utilize an attitude reference system based on a four-parameter strapdown computation which allowed utilization of an all-attitude eigenaxis maneuvering scheme.

During the mission, two of the nine original APCS RGs, the star tracker, one CMG, and one EPCS RG failed. Three additional APCS RGs were seriously degraded. However, sufficient built-in redundancy was available to accommodate all these failures while satisfying all pointing and maneuver requirements. Six additional RGs were taken into orbit and installed in the system by the second crew. This was done to provide additional capability in the event of more RG failures.

The APCS performed a central role in the survival of Skylab after loss of the micrometeoroid/thermal shield and one OWS solar wing. The built-in APCS flexibility allowed off-nominal vehicle attitude maneuvers to be performed for vehicle thermal control until a sunshade could be deployed by the first crew. Although these maneuvers required considerable TACS fuel, it was possible to complete the expanded 271-day mission and also to meet the additional maneuver requirements imposed by experiments to study the comet Kohoutek and perform stellar X-ray photography during the last mission. Skylab proved to be a major advancement in the state-of-the-art of orbital space vehicles [ 11 ].

George C. Marshall Space Flight Center  
National Aeronautics and Space Administration  
Marshall Space Flight Center, Alabama, November 1974

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