Flight Performance of Skylab Attitude and Pointing Control System

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This paper reviews briefly the Skylab Attitude and Pointing Control System (APCS) requirements and how they became altered during the pre-launch 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, are then described. The APCS' ability to overcome these failures and meet mission changes is presented. The large, around-the-clock support effort on the ground also 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.

Introduction

THE initial system requirements of the Apollo Telescope Mount (ATM) configuration, control philosophy, and operational modes of the Skylab Attitude and Pointing Control System (APCS) was defined by Chubb, et al.[1] This paper will review the initial and final APCS requirements and goals and their relationship.[2-9] The actual flight mission (and its alterations during the flight) and known achieved APCS performance will then be presented.

On May 14, 1973, the unmanned Skylab Orbital Workshop (OWS) was launched from the Kennedy Space Flight Center. Serious hardware failures began to occur during ascent through the atmosphere and their spectre continued to haunt both the astronauts and their ground-based support team.

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.

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. Three separate stages of development—the Free-Flying ATM, the Workshop Attitude Control System (WACS), and, finally, the Wet Workshop—characterized the initial design.

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Requirements

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

Clustering the ATM to the OWS imposed additional requirements on the PCS. Increased control moment gyro (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 capability of ±120° was added to the canister. To preclude CMG saturation, a Command and Service Module (CSM) Reaction Control System (RCS) 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 separate 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 two-degrees-of-freedom gimbal system using frictionless compensated flex pivots. These were designed to allow ±2° of rotation about the Experiment Pointing Control System (EPCS) X- and Y-axes.

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 rate gyro (RG) outputs were used to obtain attitude error information. Because of the canister roll capability, resolvers

Table 1 APCS requirements

	Initial APCS Reqmts. X&Y,Z (arcsec)	CMG PCS X&Y,Z (arcmin)	Final Design EPCS X&Y,Z (arcsec)	Final Design Z-LV X&Y,Z (deg)
Command uncertainty	±2.5,600	±6,10	±2.5,600	±2.5
Stability (15 min)	±2.5,450	±9,7.5	±2.5,450	N/A
Jitter (ls)	±1,60	N/A	±1,180	±0.05

were provided to transform the gyro rates to the cluster coordinate system. The Z-axis attitude errors for the cluster were obtained by integrating the vehicle-mounted Z-axis RG.

Attitude error signals for the EPCS were derived from the fine sun sensors (FSS), and rate damping was provided by the canister mounted RG's. 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 PCS and CMG error processing.

Reliability considerations for long-duration mission times caused a new look to be taken 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 transfromation 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, it would greatly simplify the program by eliminating extensive program and technical requirements. The capability to reduce program cost and complexity by eliminating ATM as a free-flying module, the ability to rapidly activate the workshop by pre-installation 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-dry workshop.

The PCS and WACS were designed to operate autonomously during separate mission phases; however, the wet-to-dry conversion made a marriage of the two systems desirable. This new system was renamed the APCS. Because of its 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 vehicle moments of inertia had increased almost tenfold 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. But now two-CMG operation had become extremely marginal (80% 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% (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] The Z-local vertical requirements were added also. The requirements for the Z-local vertical (ZLV) mode of operation (e.g., during earth resources experiments) are the same as shown in Table 1 except that a navigation error of $\pm 2°$ is acceptable.

System Description

Introduction

The cluster and its associated control axes are shown in Fig. 1. The APCS provides three-axis attitude stabilization and maneuvering capability for the vehicle throughout the mission

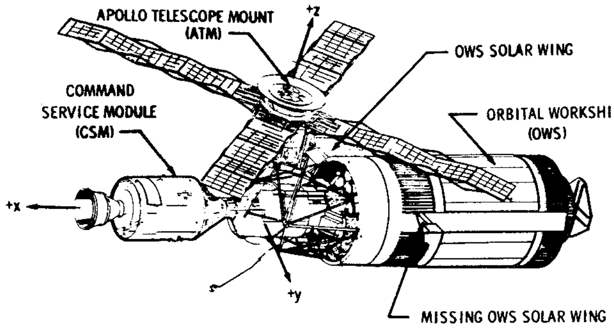

Fig. 1 Skylab cluster.

and 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 Fig. 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 CMG's, cold-gas TACS, and the EPCS.

Six control modes were addressable by Control and Display (C&D) console switches and Digital Address System/Digital Command System (DAS/DCS) for APCS operation: Standby, Solar Inertial (SI), Experiment Pointing, Attitude Hold CMG, Attitude Hold TACS, and Z-LV.

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 the TACS providing assistance if the CMG's 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 the two ASS's and nine RG's (three per axis).

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 were 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 one second. The MIB firing time was selectable from 40 to 400 msec to compensate for pressure decreases in the TACS cold-gas supply tanks. At the beginning of the mission, a thruster produced 440 N (100-lb force). This decreased to approximately 44 N (10-lb force) at the end of the mission.

CMG control system

The CMG system was composed of three orthogonally mounted, double-gimbaled CMG's with a stored momentum capability of approximately 3000 nm sec (2200 f/lb/sec) each, as shown in Fig. 3.

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

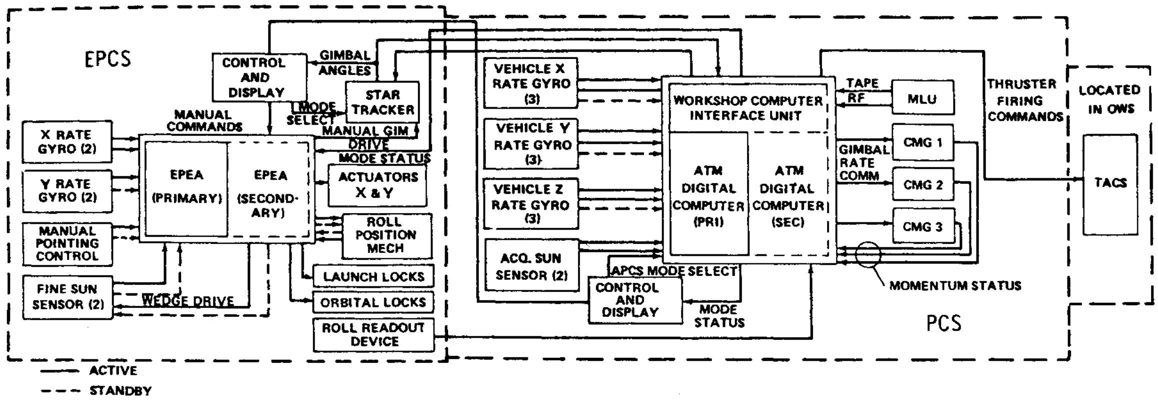

Fig. 2 APCS block diagram.

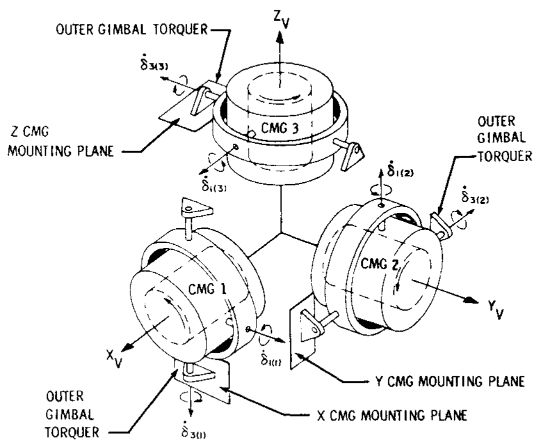

Fig. 3 CMG orientations.

gimbal stop avoidance law. Additional 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, an attitude perturbation was allowed while this gimbal was driven to the desired gimbal polarity.

PCS operation

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

The Skylab used a four-parameter strapdown attitude navigation system consisting of RG's 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 into 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 ($\pm 4°$) 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.

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 sec, and the remaining functions once per sec.

CMG momentum management

Noncyclic disturbance torques would result in a net angular momentum buildup of the CMG's. Because of finite storage capacity of the CMG's 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 *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 CMG's) momentum four times during the day portion of the orbit.

Experiment pointing control system

The EPCS was used for pointing control of the ATM experiment package.[10] It provided automatic stabilization of the experiment package about the *X*- and *Y*-axes. The FSS and RG sensor 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 was 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 Experiment Pointing Control (EPC) and EPC-related functions were canister caging control, experiment alignment calibration, and experiment and FSS door control (see Fig. 2).

Redundancy Management

All mission-critical single-point failures were eliminated.[10] 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 RG's (three per axis), two ASS's (two channels per axis), three CMG's (two required for control), two ATMDC/WCIU units, two TACS thruster modules with quad-redundant solenoid valves, two FSS's (two channels per axis), two CMG input assemblies, four canister RG's (two per axis), EPEA with two 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.

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 which calculated the maneuvers to be performed by Skylab.

Operations

Mission and Performance Description

Planned mission

The planned mission sequence was to place the unmanned Skylab, less the CSM, into a near-circular, 435-km orbit with a nominal inclination of 50° by a two-stage Saturn V launch vehicle.

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 utilizing one of the experiment cameras was conducted in orbit. The results of the test are shown in Table 2 and are well within the design requirements. The performance of the EPCS was also exceptional.

Experimenters reported that resolutions of approximately one 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.

Major Variations from Expected Operations

Micrometeoroid/thermal shield failure

At 63 sec after liftoff of the unmanned Skylab Orbital Workshop, an unexpected telemetry indication of micrometeoroid/thermal shield deployment and separation of the solar array wing no. 2 beam fairing was received. The shield had vibrated loose and torn away, carrying with it one solar array wing and leaving debris which prevent deployment of the other wing. Launch of the first crew was delayed ten days while 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 caused by the loss of the shield. The Mission Evaluation Report,[10] in addition to detailing the flight performance of Skylab, contains a history of the efforts on the part of the flight controllers and the mission support teams to keep Skylab alive until the flight crew could make the necessary repairs.

Rate gyro problems

Within the first 21 hr of APCS operation, failures of either telemetry measuring circuits or heat control circuits were evident on four rack RG packages (RCP). Later in the mission, an additional rack RGP and one EPCS RGP showed identical symptoms. After detailed studies, it was concluded that the six RGP's had experienced heat control failures causing them to overheat. All of the hot RGP's showed much noisier outputs than the normal RCP's. Another problem noted with the hot RGP's was a change in scale factor. This caused redundancy management rate integral discompares 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 tests, the cause was proved to be a design deficiency. Use of a fiber washer which shrank in the space environment 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

Table 2 Pointing accuracy data

	x	y	z
Stability (m per 25 min)	1.8	0.5	0.5
Jitter (m, worst case excursion)	±0.6	±0.45	±0.5

switchover to ATMDC control. Drift rates as high as 18°/hr were noted. The high drift rates make it difficult to maintain the correct attitude for thermal control during the first ten days. Constant drift rates could be compensated by ground command to the ATMDC. However, the drift rates changed suddenly and caused difficulty until the new rates could be measured and compensated. 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. This 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 RG's. Two of the Y-axis RG's had shown full-scale oscillation, and a Z-axis RG had failed hard-over. Additionally, another Z-axis and one other 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 RG's 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 RG's (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 RG's. The package was brought up by the second crew and 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 RG's 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 RG's after installation was excellent, and there were no more significant RG problems for the remainder of the mission.

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 #3 went from nominal to zero within one second. The spin motor currents and the bearing temperatures remained nominal. This indicated a failure of the speed sensor, which 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 #2 which appeared to be self-correcting. The CMG's 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 #1. The spin motor currents were about twice normal, and the RG's mounted in the vicinity of the CMG's were very noisy, but the bearing temperature was decreasing. None of the CMG automatic shutdown levels had been reached. There was no loss of attitude control, and the ATMDC was in normal 3-CMG control. After several minutes of analysis, the mission control team declared that CMG #1 had failed and commanded the electric brake to be applied. This cut the power to the CMG and forced the ATMDC to reconfigure to 2-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 #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 1/2 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 comes on) and to high gimbal rate demands (for maneuvering). They were characterized by above nominal wheel spin motor currents, 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 CMG's. CMG #3 did not show any distresses, but one spin bearing of CMG #2 showed an ever-increasing number, coupled with an increase in severity. It was obviously only a matter of time before CMG #2 would also fail. Relief was attempted by cancelling large maneuvers whenever CMG #2 was in distress, by reducing the maximum possible gimbal rate during the desaturation maneuvers from 4°/sec to 2°/sec (via a patch in the ATMDC), 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 helped CMG #2 to last to the end of the mission.

Star tracker operation and failure

A gimbaled star tracker was used to provide experimenters with knowledge of vehicle roll attitude about the sunline to within 10 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 with 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% (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 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 RG's allowed the system to operate without updating for long periods of time.

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 CMG's and the momentum desaturation scheme would dump the accumulated momentum during the next orbital night. However, the so-called non-propulsive 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 firing as well as gimbal angle 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 always-possible gimbal reset used much TACS fuel, it was better to inhibit momentum desaturation with CMG's and desaturate with TACS directly. This was the policy until the failure of CMG #1 which aggravated the stop problems. For 2-CMG operation, the CMG's were henceforth electrically caged to a 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. While 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.

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 unexpected 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 three weeks so that 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 to prevent stray light from entering the camera. To do this, computations were performed on the ground to maneuver the vehicle so that one of the ATM solar arrays 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°, 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 reprogrammed to reduce the size of the smallest attitude bias command from 0.1° to 0.01°. The largest allowable SI attitude bias was also increased from 4.00° to 5.25° 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 performed; three rendezvous maneuvers planned, none performed; no comet maneuvers planned, 59 performed; and no celestial object maneuvers planned, four performed.

ATMDC patches

Prior to the 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. A total of 14 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.

Crew motion

Early in the first manned mission, the mission support group became concerned about wild motions on RG telemetry as shown in Fig. 4. When the crew was asked what they were doing, they said they were jogging. By running around the walls of the circumference of Skylab, similar to a squirrel in a revolving cage, the three astronauts were able to maintain an upright position. 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 crew estimated that the EPCS jitter was less than one arc sec. Further, experimenters have been very pleased with the quality of photographs taken of the sun.

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 RG's 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 canister RG's. The device was never installed, however, because no further EPC RG failures occurred.

Post mission tests

After completion of the last manned mission, CMG #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 #2. During spindown, 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

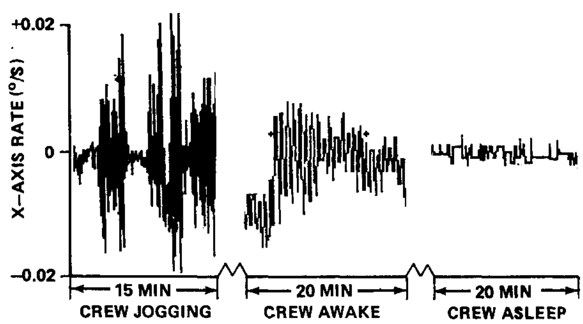

Fig. 4 Jitter caused by crew motion.

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 successfully loaded 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 attidue. 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.

Improvements/Lessons Learned

CMG rotation law

The CMG rotation law operated as desired for 3 CMG's 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° (stop-to-stop) to at least 450°. This change had been requested, but the long lead-time hardware items were too far down the road. 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 two 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.

Attitude error limiting

The maximum CMG momentum envelope is a sphere. This matches well the attitude error generation method, using quaternions which treat 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-axes, 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/sec (900 ft/lb/sec), the CMG's 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 TACS-ONLY 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 EVA's.

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 2-CMG operation, the predicted TACS impulse usage was 160kN·sec (36,000 lb-sec) for the life of the Skylab. The vehicle was loaded at launch with about 375 kN·sec (84,000 lb-sec) or 235% of the predicted (design) usage. This was fortunate since 190 kN· sec (43,000 lb-sec) or about 120% of the predicted usage was used during the first two 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 come up with 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 EVA's 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 #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, it was also pointed at Mercury (to verify comet Kohoutek pointing capability) and 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 (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 following six 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 inertial 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 was often quite large, but the desaturation scheme was flexible enough that the performance degraded only when the error exceeded 10°. The assumption of reasonable RG drift was severely violated until the installation of the six-pack RGP by the second crew. The programmed inertia 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 ATMDC software.

The attitude control law combination was quite forgiving with respect to the actual CMG momentum magnitude while assuming that it was 100% of the nominal (3 operational

CMG's) case. This was demonstrated when attitude control was not impaired when CMG #1 failed. Control system performance appeared normal, and the ATMDC redundancy management had not realized that anything was wrong. Therefore, action from the ground had to initiate two-CMG operation.

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 trouble shooting, maintenance, and repair, i.e., thermal shield deployment, freeing the OWS solar panel, 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.

Nomenclature and coordinate systems

Nomenclature and coordinate system definitions usually do not receive the proper attention *very* early in definition phases of the program. This leads to unnecessary complications. The Skylab program was no exception. Future program developers should be careful to avoid nomenclature and definition problems.

Conclusions

Skylab was the first manned spacecraft to utilize large CMG's 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 and 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 RG's, the star tracker, one CMG, and one EPCS RG failed. Three additional APCS RG's were seriously degraded. However, sufficient built-in redundancy was available to accommodate all of these failures while satisfying all pointing and maneuver requirements. Six additional RG's 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 roll 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 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.

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