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Skylab Attitude Control System

Abstract: The attitude stabilization and control system for Skylab evolved from an analog controller into a fully digital processing system. Features of this system include a software-determined attitude reference to provide general maneuvering ability, an in-orbit programming capability, the use of large control moment gyros for attitude control, and the use of vehicle maneuvers to desaturate gyro momentum. The objectives, requirements, and implementations of the control system software are described, along with the rationales for certain design decisions and discussion of some system dynamics and actual performance.

Introduction

Skylab, as a manned, Earth-orbiting space station, was primarily a research tool to gather knowledge of the space environment and of the performance, resilience, and peculiar capabilities of men and equipment in this environment. Four categories of Skylab-based activities are characteristic:

Physical science To increase knowledge of the space environment as it affects the existence of life on Earth. This involves two principal subsets of investigations: a) the sun and its effects upon the Earth; and b) the nature and effect of radiation and particles present in near-Earth space or emanating from our galaxy and other remote regions of the universe.

Biomedical science To increase knowledge of the biomedical functions of living organisms, including the human system, by observing how living organisms function under conditions different from those on Earth.

Earth applications To develop techniques for observing Earth phenomena with the perspective and rapidity that are possible only from space. Phenomena to be observed include those pertinent to agriculture, forestry, geology, air and water pollution, land use, meteorology, and the influence of man upon these ecological elements [1, 2].

Space applications To develop improved techniques for space operations in crew habitability, man-vehicle interrelationships, space vehicle structures and materials, and the evaluation of equipment required for the successful habitation of space.

The most stringent requirements on the Skylab orbiter control system were imposed by the external observations represented by the solar, galactic, and Earth survey experiments. The equipment requiring lesser accuracy, in general all except the astronomical experiments, was rigidly connected to the Skylab structure. For these experiments, the entire space station was attitude-stabilized to the required accuracy. The equipment requiring extreme pointing accuracy and stability, within a few seconds of arc, was mounted on a separately controllable structure, known as the Apollo Telescope Mount (ATM) Spar, which could move with respect to the Skylab frame. The ultimate accuracy was achieved by fine, or vernier, control of the ATM Spar with respect to the stabilized Skylab; control input was derived from sun-sensing.

• *System overview*

The Skylab Attitude and Pointing Control System (APCS) performs the functions of rotating the spacecraft to predetermined attitudes; holding these attitudes for the necessary lengths of time; and providing very precise pointing for the Apollo Telescope Mount. The mechanization of the Attitude and Pointing Control System was implemented with three interrelated sets of equipment: thrusters, Control Moment Gyros, and the vernier solar-radiation-feedback system, known as the Experiment Pointing Control System.

The primary reference system consists of rate gyros, which measure the vehicle's angular rates and derive the vehicle's attitude parameters. This system provides accurate rate control. It cannot, however, maintain a precise angular pointing reference for prolonged periods of time because of gyro drift. Therefore, this system is assisted by sun sensors and star trackers, which provide attitude reference orientation updates.

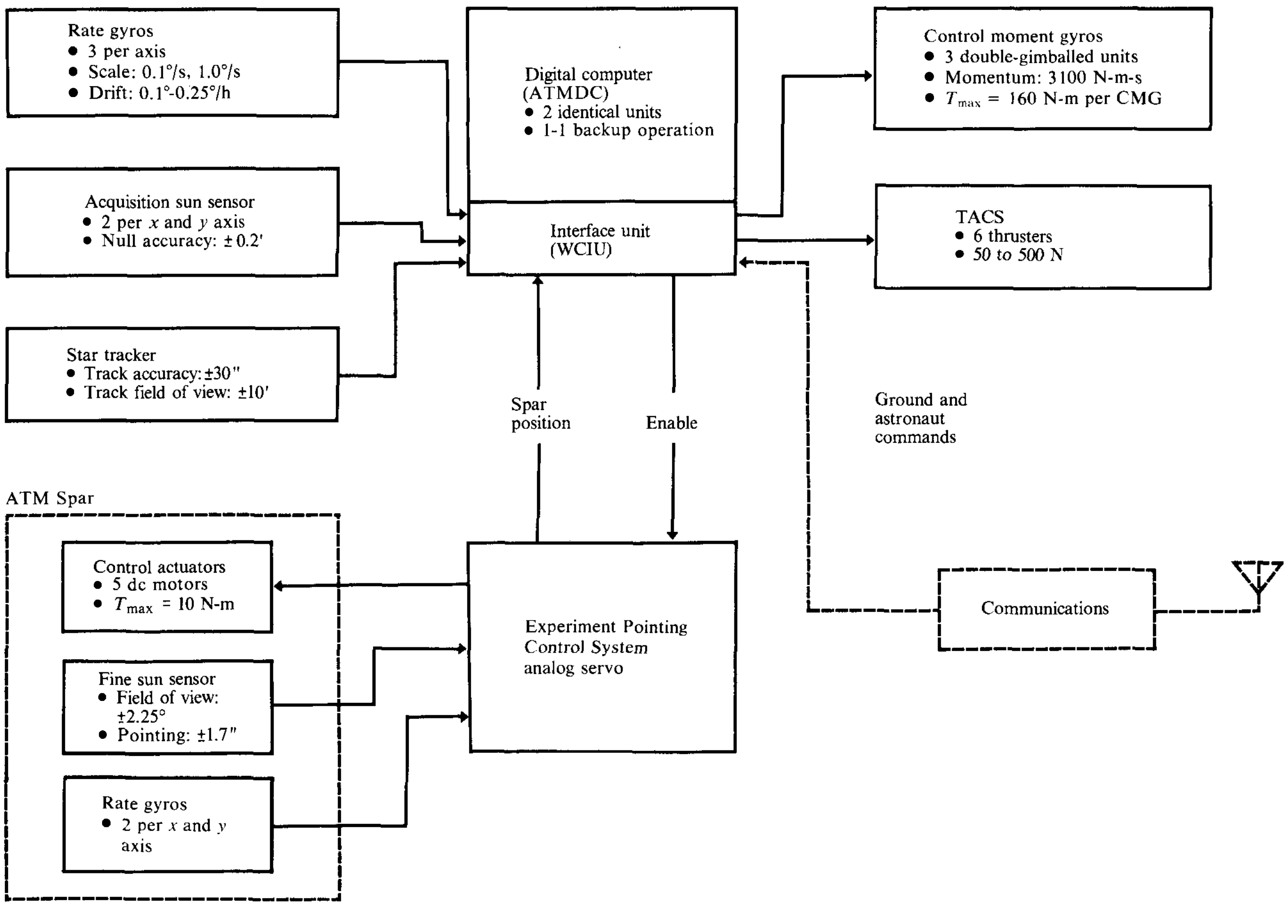

Figure 1 Functional diagram of the Skylab Attitude Control System.

The principal attitude control mechanism uses double-gimballed Control Moment Gyros (CMGs). Three gyro rotors, 55 cm in diameter and spinning at approximately 9000 rpm, are mounted in gimbals with their axes nominally mutually perpendicular. The torquing of the CMGs is controlled by a digital computer. Input to the computer, in terms of desired attitude, is supplied by the astronauts or from automatic systems.

A secondary attitude control system is provided by gas-expulsion thrusters, acting together in a Thruster Attitude Control System (TACS), which is controlled by the same digital computer and uses the same rate gyros as the attitude rate sensors.

The normal mode of Skylab orientation control is by Control Moment Gyros, with the thrusters being used to aid the CMG system when its capabilities are exceeded, or to "dump" CMG momentum, if necessary. The all-thruster (TACS only) mode is available for emergency backup. A third set of equipment, used for very precise control, is the vernier control of the ATM, also known as the Experiment Pointing Control System (EPCS), which operates "nested" within the principal control system, also under supervisory control of the digital computer that controls the CMG and TACS.

Skylab is thus the first manned space vehicle whose attitude is fully controlled by digital computer. An overall functional diagram of the system, illustrating the major characteristics of the key subsystems and components, is shown in Fig. 1. IBM's involvement in Skylab consisted of supplying the computer subsystem hardware, developing the flight software, and supporting the operational phase of the mission.

The Skylab APCS computer subsystem [3] consists of two Apollo Telescope Mount Digital Computers (ATMDCs), one Workshop Computer Interface Unit (WCIU), and one Memory Load Unit (MLU) and its associated tape recorder. Appurtenant to the computer subsystem were the design, definition, and implementation of the flight software. The problems following the liftoff of Skylab expanded a planned low-level mission support role into a 24-hour-per-day, seven-day-per-week role for the entire mission.

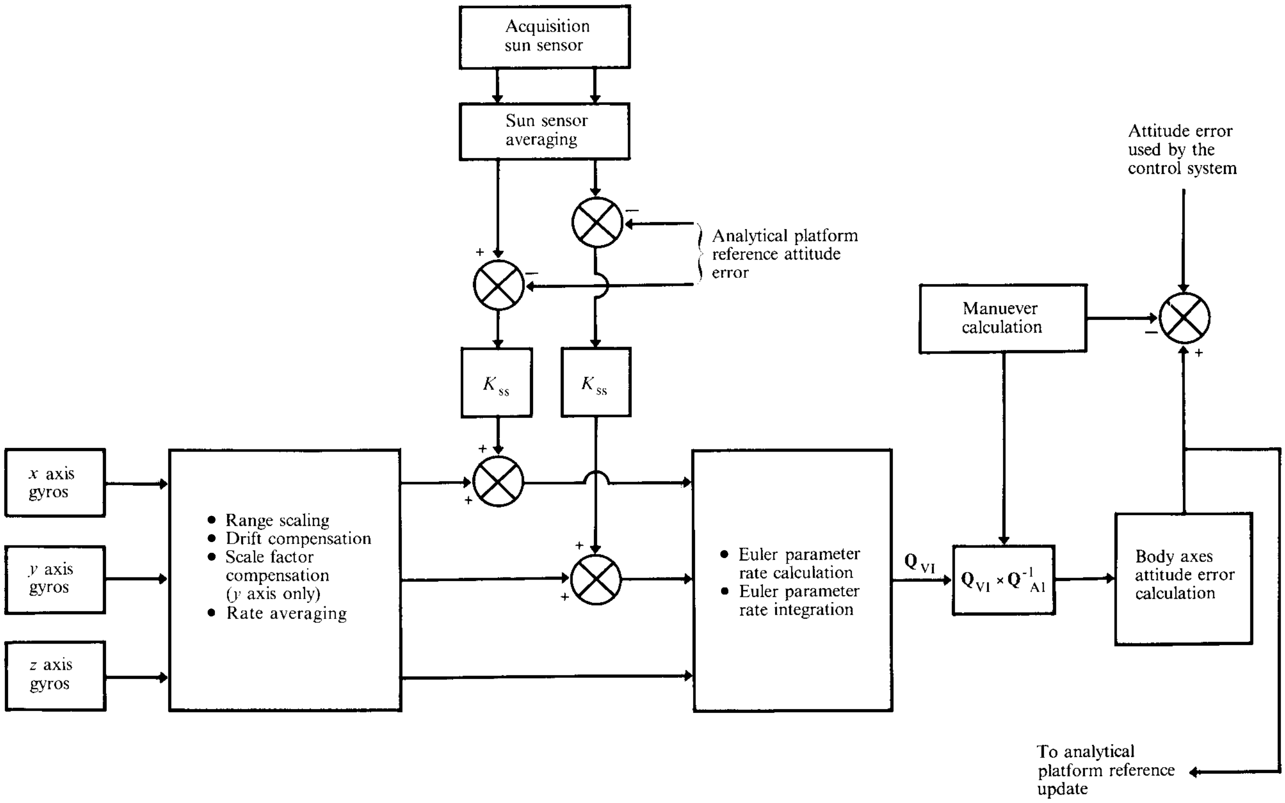

Figure 2 Functional diagram of the attitude reference subsystem.

Control system software

The ATMDC flight program served three basic functions: 1) to maintain attitude reference; 2) to compute CMG gimbal rate commands; and 3) to determine TACS firing commands when needed.

• *Attitude reference*

This portion of the program accepts rate information about each spacecraft axis, plus sun sensor data when available, and generates attitude error signals for use in CMG and TACS control. A functional diagram of this subsystem is shown in Fig. 2. For the orbiter coordinate system (body axes), the x axis is along the vehicle center line, positive in the direction of the multiple docking adapter; the z axis is parallel to the experiment spar center line, positive in the direction of the sun; and the y axis completes a right-handed system.

The rate gyro subsystem, in its normal configuration, supplies two rate signals for each axis. Every 0.2 s, each rate output is sampled and the mean taken to provide a better quality reading. The gyro has two scales: 1°/s maximum and 0.1°/s maximum. The computer automatically adjusts to the proper scale by sampling appropriate hardware signals. Ground control can supply drift compensation coefficients and limited scale factor compensation (y axis gyros only).

Normal acquisition-sun-sensor operation provides two inputs per axis (x and y axes only); their average is used as the control parameter. The sun sensors provide continuous reference updating when the sun is being tracked. The parameter K_{SS} (Fig. 2) affects control when the sun sensors are in the loop; it is set to zero when they are removed. The control loop senses any difference between the analytical platform reference and the sun sensor output (i.e., gyro drift); it then provides a correction signal to force the reference to agree with the sun sensor. This scheme was used in preference to direct sun sensor control because of the coarseness of the analog-to-digital conversion of the sun sensor output (0.006°). The high forward-loop gain of the CMG control system would cause this coarseness to produce CMG gimbal rate limit cycles of potentially harmful magnitude. Therefore, the adopted scheme provides the control system with a much smoother signal while still maintaining the desired pointing accuracy.

Vehicle attitude information is maintained in the ATMDC in quaternion form. A quaternion represents a transformation between coordinate systems obtained by a single eigenaxis rotation, and the general form of the quaternion used is

$$\mathbf{Q}_{AB} = \begin{Bmatrix} q_{AB1} \\ q_{AB2} \\ q_{AB3} \\ q_{AB4} \end{Bmatrix} = \begin{Bmatrix} \sin(\mu/2)\cos\alpha \\ \sin(\mu/2)\cos\beta \\ \sin(\mu/2)\cos\gamma \\ \cos(\mu/2) \end{Bmatrix},$$

where the first subscript indicates the system being transformed *to*, the second indicates the system being transformed *from*, and the third indexes the quaternion component. Also, μ is the eigenaxis rotation angle, and α, β, γ are the angles between the x, y, z axes, respectively, and the eigenaxis.

The relation between the vehicle and the solar inertial attitude is represented by $\mathbf{Q}_{VI}$, which is computed by calculating and integrating the individual Euler parameters [4, 5]. To compensate for cumulative round off effects, $\mathbf{Q}_{VI}$ is normalized once per orbit.

The desired attitude of the vehicle relative to the solar inertial attitude is represented by $\mathbf{Q}_{AI}$. The parameters that affect the computations related to this quaternion are discussed in the *Maneuver mechanization* section of this paper.

The third quaternion, $\mathbf{Q}_{VA}$, represents the vehicle's axes in relation to the desired orientation axes and provides the means by which attitude errors are determined. This quaternion is formed by multiplying $\mathbf{Q}_{VI}$ by $\mathbf{Q}_{AI}^{-1}$.

The flight program utilizes a special class of quaternions whose norm is one. Those four-element vectors have characteristics similar to transformation matrices since the transformation operation does not alter the magnitude of the vector being rotated. Quaternions were chosen because of the unique ability of digital computers to efficiently perform quaternion algebra, thus reducing storage requirements over the use of direction cosines; they also avoid the singular points inherent in Euler angles. Details of the computational methods and the equations used in the calculations may be found in [4, 5].

The attitude-reference computational accuracy requirement is that the eigenaxis rotation (represented by the attitude reference quaternion) not drift, because of the software, more than 0.15°/h when operating with fine scale rate-gyro readings, or 1.5°/h when operating with coarse scale readings.

The cumulative roundoff effect (computational drift) was tested prior to delivery of the final flight program by using both the actual flight program and a simulation model of the program. Tests were run at high and low rates both during maneuvers and while maintaining an inertial attitude. The results showed the attitude reference drift to be less than 0.15°/h for all tests, most cases being less than 0.1°/h. An accuracy test made during the Skylab mission, using attitude information from the star tracker, indicated actual drift values of approximately 0.03°/h.

• *Control Moment Gyros*

The basic CMG control loop is shown in Fig. 3; it illustrates the sample-data control system wherein analytical platform reference attitude errors and body axis rate gyro outputs are used to determine the control torque required. The sample rate, five samples per second (sps), is significantly higher than the system response; thus, the system control characteristics can be approximated by the following linear parameters for natural frequency and damping ratio [6]:

$$\omega_i = \sqrt{K_{0i}H/I_i},$$

$$\zeta_i = K_{1i}/2\sqrt{K_{0i}H/I_i},$$

where the I_i represent the principal-axis moments of inertia; H is the nominal momentum of a CMG; the K_i are the gain factors; and $i = x, y, z$. The natural frequency and damping ratio were held constant for the various Skylab configurations, by means of software modifications of K_0 and K_1, at approximately 0.017 Hz and 0.7, respectively, for all axes. The equations for natural frequency and damping ratio are valid because the digital filter, the CMG steering law, and the CMG gimbal response all have a sufficiently high bandpass so that dynamic factors are not introduced in the control frequency region. The torque commands are digitally filtered to minimize undesirable effects from the flexible-body dynamics. The digital filter equations [7] are solved every 0.2 s.

The limit, shown symbolically in the attitude channel (Fig. 3), provides rate maxima for the CMG system response characteristics. Establishment of a value for those limits is important: They constrain the rate, and therefore the CMG momentum change, at which the Skylab can respond to attitude offsets; too large a momentum change would cause the CMGs to encounter gimbal position stops. The selected rate limits are 0.08°/s for the x axis, 0.03°/s for the y axis, and 0.037°/s for the z axis.

The primary design requirement for the CMG control law was to develop CMG gimbal rate commands such that the resulting precessional torques on the vehicle would equal the desired control torques. The principal system and hardware constraints are as follows:

1. The system must operate with either two or three Control Moment Gyros.
2. CMG momentum vector excursion is limited by the gimbal position stops.
3. Upper limits exist on the commandable gimbal rates.

These requirements and constraints were satisfied by a scheme developed by Kennel [4].

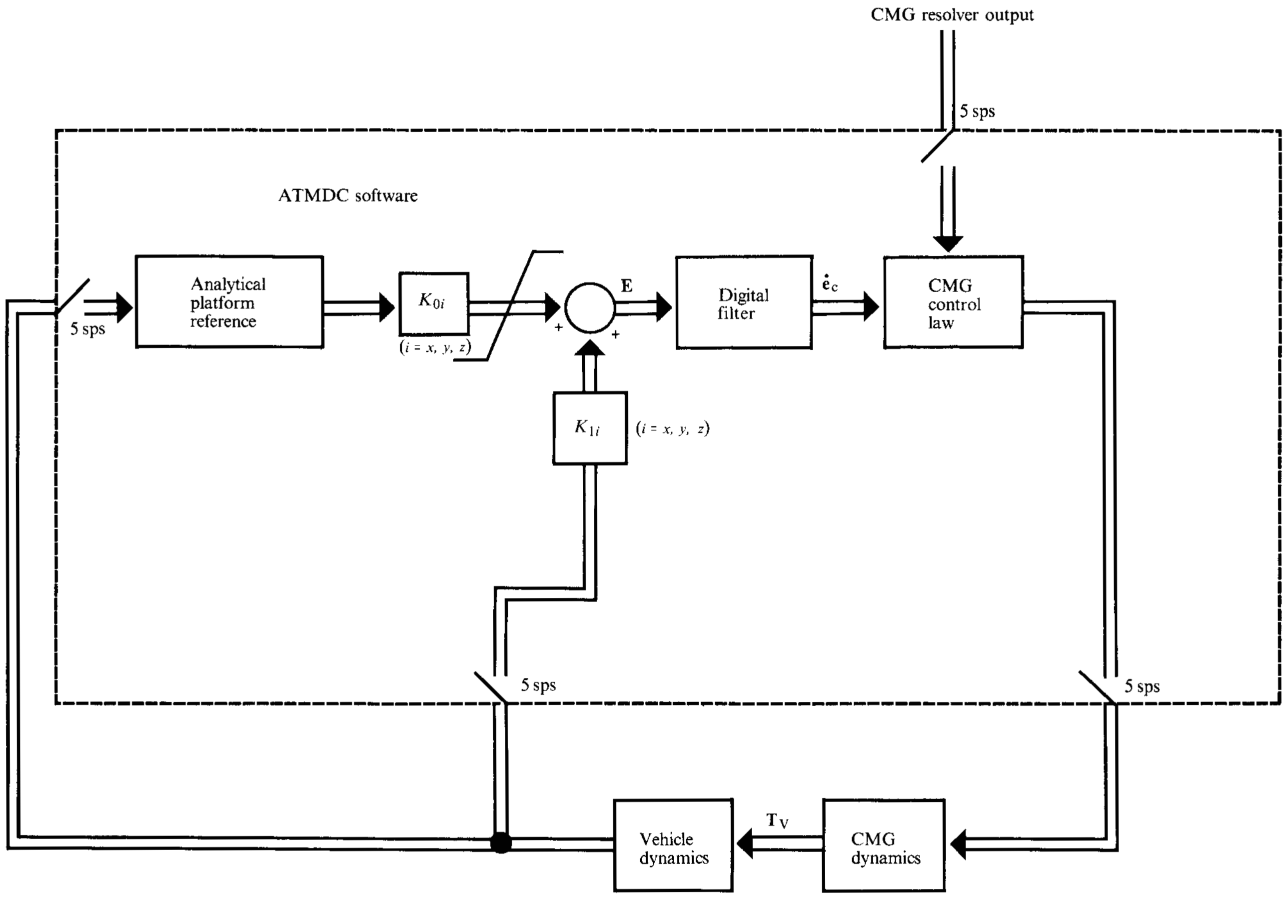

Figure 3 Control Moment Gyro control loop.

The definition of the gimbal angles for the CMG configuration implicitly assumes that each CMG is nominally aligned along each vehicle axis. The required input to the control law is the control torque command, $\dot{\mathbf{e}}_c$. The control law is governed by the relation $\mathbf{T}_V = -\dot{\mathbf{H}}_T$ [4, 5], where $\dot{\mathbf{H}}_T$ is the rate of change of the CMG momentum vector with respect to inertial space and $\mathbf{T}_V$ is the CMG control torque imparted to the vehicle. The problem is how to effect the $\dot{\mathbf{H}}_T$ corresponding to the command control torque so that $\mathbf{T}_V = \dot{\mathbf{e}}_c$. A single CMG cannot satisfy this condition since there are only two degrees of freedom per CMG and three vehicle axes to control; at least one CMG pair is required. If the CMG is unconstrained by gimbal position limits, it can be assumed that commanded and actual gimbal rates are equal; this is a consequence of the approximately 5-Hz bandpass of the CMG gimbal dynamics.

There are three possible pairing arrangements for a three-CMG configuration: Pair A contains CMGs 1 and 2; pair B, 2 and 3; and pair C, 3 and 1. Each momentum vector pair handles its share of the torque command by splitting it into two components, one perpendicular to the vector sum of the CMGs and the other parallel to the sum. The first component results in a rotation of the pair as a unit; the second component results in a scissoring action of the two CMG vectors with respect to each other. The splitting of the torque command emphasizes the particular pair which at that instant has the greatest capability of producing a torque in the desired direction. Gain functions G_i are set up for each of the possible pairs [4, 5]:

$$G_i = |\mathbf{H}_{\mathrm{p}i}|^2/(|\mathbf{H}_{\mathrm{PA}}|^2 + |\mathbf{H}_{\mathrm{PB}}|^2 + |\mathbf{H}_{\mathrm{PC}}|^2),$$

where $\mathbf{H}_{\mathrm{p}_i}$ is the vector cross product of individual momentum components, and the torque command applied to each pair can be written as $\dot{\mathbf{e}}_{c_i} = G_i\dot{\mathbf{e}}_c$, $i = $ A, B, C.

The software is structured so that if for any reason power is removed from a CMG, the direction cosines for that particular unit are set to zero. This nulls the $\mathbf{H}_{\mathrm{p}_i}$ for the two pairs in which the affected unit participates and also nulls the gain G_i so that the total torque command is applied to the proper CMGs. In this manner, the software automatically switches from three-CMG to two-CMG operation.

The presence of gimbal stops requires additional logic in the control law in order to develop individual momentum component rotation terms that maintain a satisfactory gimbal angle configuration. Encountering of the mechanical gimbal stops is prevented, without producing a torque that will disturb the vehicle, by the rotation of the individual momentum components around their vector sum. This part of the control law is known as the rotation law [4, 5].

The next function of the control law is to transform the momentum rotation vectors into the appropriate gimbal rate commands for implementation by the CMG velocity servo loops. The commanded gimbal rates are constrained to avoid the phenomenon known as "backtorquing" within the loops. A 4°/s limit was established on the inner gimbal rate commands, the outer command limit being a variable whose value depends on the position of the inner gimbal. When the inner gimbal position is 0°, the maximum amount of torque is transferred between the inner and outer gimbals; the limit value on the outer gimbal rate is 7°/s.

Normal operation of the CMG control system, i.e., maintaining an inertial hold mode that responds only to gravity gradient torques, does not produce gimbal rates that approach the limits. Maneuvering or impulsive torque situations, however, can cause the limits to be reached. When a rate limit on any gimbal is broached, all gimbal rates are reduced by a proportionate amount. This action retains the no-cross-coupling philosophy of the control law but reduces the total loop gain of the control system.

Tests were made during the mission to determine whether the CMG control system could be used to point the ATM experiments to the comet Kohoutek. The results showed that attitude excursions were less than 2.8 arc-minutes peak to peak, which was better by a factor of two than the accuracy specification of ± 6 arc-minutes. After 193 days of operation, one of the CMGs failed. The CMG control system proceeded with the automatic reconfiguration for two-CMG operation and successfully fulfilled the system requirements for the remainder of the mission (78 days, during which nearly 100 maneuvers were performed with no degradation in experimental data due to pointing errors).

Thruster Attitude Control System

There are two mutually exclusive applications of the Thruster Attitude Control System (TACS): 1) to provide attitude control of the Skylab based on attitude and attitude-rate error information, and 2) to provide momentum desaturation impulses for the CMG control mode.

The first mode is known as TACS-only control. The decision to issue thruster firing signals is determined by limit-checking a linear combination of attitude and attitude-rate errors [5]. Three options are available: 1) a dead zone for no firing; 2) a region in the phase plane of minimum impulse firing, maintained at 22 N-s (the impulse unit is newton-second), and 3) a region for firing for the full slow loop cycle of 1 s. Since the thrust decreases as fuel is depleted, the on-time for a minimum impulse firing is periodically changed by ground command to maintain the desired 22 N-s impulse.

A limit is imposed on the attitude error parameters used in computing the linear combination of attitude and attitude-rate errors; this is done to conserve TACS fuel in responding to large attitude errors. The rate-error signal is composed of a digitally filtered rate-gyro input combined with a commanded vehicle rate. The digital filter implementation is similar to that in CMG control but with different dynamics and a bandpass of approximately 0.2 Hz. The design criteria eliminate undesirable vibration effects, yet allow sufficient response to prevent unnecessary consecutive opposing firings. For normal TACS-only control operation, a ratio of 10 to 1 between the attitude and attitude-rate gains is used.

The second TACS function, to provide a desaturation impulse when the CMG system is saturated, becomes operative when the total system momentum exceeds 96 percent of the available CMG capability. Total system momentum is calculated by the computer on a per-axis basis. Comparison of the magnitude of the total system momentum with an appropriate threshold (depending on whether two or three CMGs are being used) determines whether a TACS impulse is required.

Engine selection is based on determining which thruster will reduce the magnitude of the maximum system momentum component. The thruster on-time is based on integral multiples of the basic minimum impulse firing time: For each half-unit of nominal CMG momentum magnitude by which the system momentum exceeds the desaturation threshold, the multiplier is increased by one. For example, a momentum deficiency of one-half to one unit causes two minimum impulse firings. Use of total system momentum rather than CMG momentum alone in the desaturation firing criteria has a beneficial effect on TACS fuel conservation. This scheme allows the CMG system to remove certain attitude errors without firing the TACS; e.g., if the CMG system is saturated but the vehicle rate is in the right direction, the total system momentum might not be saturated.

During the mission TACS served its purpose as a backup control system and as a source of momentum relief for the CMG control system. The TACS was utilized beyond premission planning because of the unexpected events that occurred during the beginning of the mission (meteoroid shield failure during liftoff) and was exclusively used to desaturate the CMG system in an unplanned manner during the first 12 days of the mission since the Skylab orientation was constrained by thermal and power considerations that prevented desaturation of the CMGs by vehicle maneuvers [8].

• *Special control situations*
Two additional control system functions implemented in the Apollo Telescope Mount Digital Computer are the CMG "caging" function and the CMG reset function. Caging is the process by which the CMG momentum vector is set to predetermined values. The reset function is the mechanism by which the CMG system automatically reconfigures itself to a desired momentum state and gimbal angle configuration if, due to abnormal circumstances, a gimbal should hit its limit stop. Although the CMG caging and reset functions were originally included in the flight program as protective measures, and their use was expected to be minimal, during the mission the reset routine was actually used to dump CMG momentum, force particular CMG gimbal angle trajectories, and eliminate thruster firings during experiments that required fine pointing control.

Caging is accomplished in two steps. The first step, lasting 60 s, returns the CMG gimbal angles to the control law neutral position [5]. The second step applies the steering law to force the desired momentum state. This is done by synthesizing the control torque command $\dot{\mathbf{e}}_c$ from the scaled difference between the desired momentum state and the actual momentum state. The control law operates to null the error signal and, within 20 to 30 s, positions the CMG momentum in the desired direction.

A reset routine is automatically entered upon sensing a gimbal stop encounter that would impair CMG control. It is a four-step process, the first two of which, lasting 100 s, represent CMG caging. The caging momentum is computed as a function of the orbit geometry and represents the desired CMG momentum state at that particular time. A third phase, lasting 60 s, utilizes the TACS in a rate-only mode to reduce the vehicle rates that result from the caging process. This is accomplished by the software by setting the coefficients of the TACS gain equation to values that represent the threshold below which the rate is to be reduced. The fourth phase reenables normal CMG control, which compensates for any residual attitude error produced in the first three phases. If there is no vehicle rate upon entering the last phase, the resulting CMG momentum state, after closure of the attitude error, would be the computed desired momentum state. The third phase, however, only reduces the vehicle rate below a threshold (0.02°/s, x and z axes; 0.01°/s, y axis) and there exists, in general, a difference between actual and desired momentum upon completion of the routine. For the rate thresholds used, momentum errors up to 0.33 of the nominal momentum of one CMG are permissible.

Maneuver mechanization

Skylab was required to maneuver in response to Attitude and Pointing Control System mode changes and attitude maneuver commands, and to effect momentum desaturation of the CMG system. These maneuver requirements are met in either of two ways: generation of attitude reference offset commands (E_x, E_y, E_z) or generation of a new desired attitude reference, $\mathbf{Q}_{\mathrm{AI}}$. Figure 2 indicates where these parameters enter the control loop. Maneuvering via offset attitude commands is restricted to small angle displacements relative to a stationary reference. These maneuvers are treated by the control system as an initial-condition response. Arbitrary magnitude displacement angles or maneuvers relative to a moving reference require computation of the desired attitude reference quaternion. These latter maneuvers are implemented with the control system operating in a rate-only mode, in which the commanded control torque parameter is proportional to rate error. The vehicle is forced to rotate about the indicated eigenaxis (if TACS-only, to within a certain threshold). The processing required to generate the control signals and to configure the control laws for the principal maneuver situations is discussed below.

• *Attitude offset maneuver*
This maneuver provides offset pointing about the x and y axes when Skylab is in the solar inertial mode; the offset is limited to ±4°, the linear range of acquisition-sun-sensor operation. It is also used for CMG desaturation. The desaturation method [9] uses gravity gradient torques produced by angular maneuvering. The required maneuvers are computed from CMG momentum data (direction cosine resolvers) taken at four discrete points in an orbit. From these data, bias offset or ramp components in the cyclic variation of the CMG momentum are calculated, thus determining the amount of momentum to be dumped.

• *Maneuvering to a desired attitude reference*
This technique represents the general Skylab maneuvering capability in which any arbitrary attitude can be obtained; e.g., the solar inertial attitude can be reacquired from an arbitrary position, or the vehicle can be aligned in a given relation to the orbit radius vector. These types of maneuvers are completed within a fixed amount of time. The chosen implementation satisfies the following criteria: 1) preserve maximum commonality among the various maneuver situations to minimize computer memory usage; 2) tolerate imperfect control that could result from gimbal stops for a short period of time; and 3) make efficient use of TACS impulses.

Upon maneuver initiation, an elapsed time counter t' is set to zero and the desired attitude relative to the solar inertial quaternion is determined. Attitude error is then divided by the desired maneuver time t to produce command rates for each axis ($\dot{E}_x$, $\dot{E}_y$, $\dot{E}_z$). The control laws (either CMG or TACS-only) are configured for rate-only control (attitude gains set to zero). Subsequent flight program passes increment t' every 0.2 s and the command rates are computed [5]. To maintain a safe level of structural loading, a limit of 0.3°/s is imposed on the commanded eigenaxis rate by root-sum-squaring the E_i components and limit-checking. If the limit is exceeded, all components are scaled proportionally so that the commanded eigenaxis rate equals 0.3°/s. While the command rates are being limited, t' is not incremented.

A maneuver to an arbitrary position is accomplished with the vehicle in the attitude-hold mode. The ATMDC receives a maneuver command with three associated data words representing x, y, and z axis attitude displacements. Each maneuver command is relative to the previous desired attitude and assumes a y, z, x Euler rotation sequence [5]. The data command can be entered in either of two ranges, with a resolution from 0.1° to 51.1°, or from 1° to 180°.

A *z/Local Vertical (z/LV) mode* for Earth resources experiments is defined as a mode having the z (yaw) vehicle axis pointing along the orbit radius vector. In this mode the flight software determines the position in orbit to acquire the z/LV attitude. Once the vehicle is at that position, $\mathbf{Q}_{AI}$ is rotated to correspond to the movement of the radius vector. The initial determination of desired attitude is given by [5]

$$\mathbf{Q}_{AI} = \begin{Bmatrix} 0 \\ \sin(\Delta\eta_{ty}/2) \\ 0 \\ \cos(\Delta\eta_{ty}/2) \end{Bmatrix} \begin{Bmatrix} -\sin\,(\eta_x/2) \\ 0 \\ 0 \\ \cos\,(\eta_x/2) \end{Bmatrix} \begin{Bmatrix} 0 \\ 0 \\ -\sin\,(\nu_z/2) \\ \cos\,(\nu_z/2) \end{Bmatrix},$$

where $\Delta\eta_{ty}$ represents the rotation about the vehicle y axis required to place the projection of the z axis along the radius vector in time t; η_x is the solar elevation from the orbital plane; and ν_z is the displacement of the x vehicle axis from the orbital plane. Upon completion of the maneuver, $\Delta\eta_{ty}$ is made to vary at the orbit rate. Upon obtaining the proper attitude, the control system is commanded at orbit rate to maintain that attitude. Premission studies indicated that it was preferable to begin ramping the orbit rate command prior to $t' = t$ to minimize control system transients. Therefore, a linear function with a ramp input from zero to orbit rate is added to the $\dot{\mathbf{E}}$ beginning 60 s before $t' = t$. The flight program can also offset-point in the z/LV mode. This involves basically the same operations as for the attitude-hold maneuver and the same resolution and maximum command angle options are available and can be implemented by the digital command system.

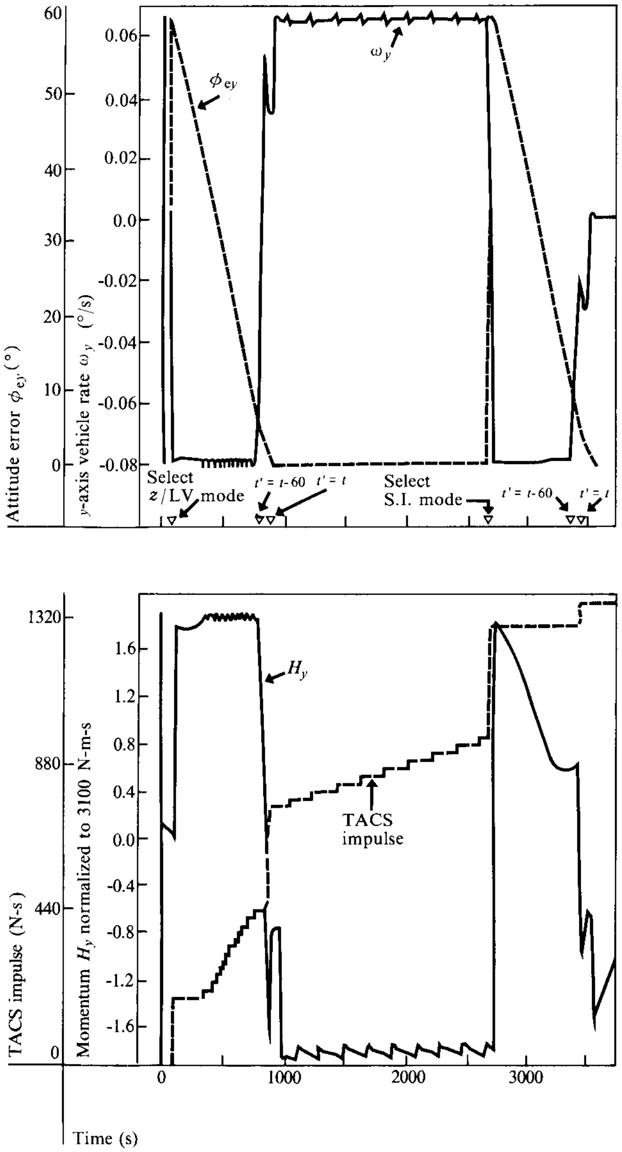

Figure 4 Diagram of typical maneuver characteristics.

• *Typical response characteristic*

Figure 4 shows the key performance parameters for a typical maneuver situation. A value of $\eta_x = 0$ was chosen for simplicity (x, z rate requirements are essentially zero and are not shown) with a typical maneuver time of 13 minutes. The maneuver to z/LV mode was initiated 20 orbital degrees before the sunrise terminator, and the maneuver back to solar inertial attitude started 60 orbital degrees past orbit noon. Two-CMG control is shown to better illustrate the TACS usage. Noteworthy in the figure are 1) the linear ramp-down of attitude error, 2) the constant vehicle rate, 3) the sloping down of the rate beginning 60 seconds prior to the end of the maneuver time (the control system reverts to attitude-plus-rate operation at the end of maneuver time), and 4) the utilization of the TACS impulse prior to CMG saturation. These events are generally present in all maneuver situations.

Summary

The initial concept of the Skylab attitude control system was that of an analog controller with a very limited maneuvering capability. From that concept, the attitude control system evolved into a fully digitized system with a general maneuvering capability. The versatility of the all digital attitude control system was demonstrated during the mission when alternate methods had to be operationally devised within the framework of the existing software to keep the CMG control system from saturating. In addition, the attitude reference system was forced to operate with rate gyros, some of which drifted as much as 17°/h (0.1°/h specification).

The TACS impulse budget for Skylab prior to launch was based upon fewer than 40 z/LV maneuvers and only a few attitude-hold maneuvers. Because of the loss of the meteroroid shield, the failure of one CMG in flight, the occurrence of comet Kohoutek, and an increased emphasis on Earth resources experiments, Skylab performed approximately 80 z/LV maneuvers and approximately 130 attitude-hold maneuvers during the mission. The capability of accommodating that many maneuvers with a restricted impulse budget typifies the performance characteristics and versatility of the maneuvering scheme mechanized by the flight software.

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