SYNCOM Satellite Program

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Two SYNCOM spacecraft have been launched, and a third is planned for a synchronous equatorial orbit in the second quarter of 1964. The results of this experimental program are discussed, and the design improvements incorporated into each successive vehicle, as a result of spaceflight experience, are summarized. Design features of communications satellites now under development are also mentioned.

SYNCOM, a spin-stabilized spacecraft, was developed for NASA to show the feasibility of using synchronous 24-hr orbits for communications satellites. One of the main purposes of the program was to demonstrate the techniques for placing such a satellite in a circular orbit at an altitude of 22,300 statute miles. Other objectives were to move it to a desired longitude, to make adjustments in attitude to direct the antenna beam, and to keep it on station or synchronized under continual view of ground stations. To accomplish these and other goals, three flight vehicles were built with the design constraint that they be put into orbit with the Thor-Delta launch vehicle using the payload rocket motor and jet control to effect the remaining orbital maneuvers. Descriptively, SYNCOM is a spin-stabilized, active-repeater communications satellite utilizing redundant transponders, telemetry, command, and control systems. It is powered by solar cells having an initial output of 30 w and by batteries that primarily provide current surges for the rocket motor igniter squibs and pulse-jet solenoids. A cutaway view of the SYNCOM spacecraft is shown in Fig. 1.

SYNCOM 1, launched in February 1963, was successfully injected into a nearly synchronous orbit, but during the final second of the 21-sec apogee motor burning, contact with the craft was suddenly lost. No further contact, other than several faint optical sightings, has ever been made. Postlaunch analyses and testing led to the conclusion that a high-pressure nitrogen tank failure caused the loss of this first spacecraft.

Design changes were made in the remaining two spacecraft to preclude a recurrence of the SYNCOM 1 experience. These included 1) greater clearance between the nitrogen tanks and adjacent structure to eliminate any possible contact under vibration, 2) reduction of the nitrogen system operating pressure from 3670 to 2500 psi to lower tank stresses, 3) a new wiring harness having redundant wires in all critical circuits to minimize the likelihood that an open circuit could cause a total power failure, and 4) a standby battery was added to provide 40 min of telemetry, should the main power supply fail. With these improvements, SYNCOM 2 was put into orbit on July 26, 1963, and it has since achieved an impressive record for continuous operation without malfunction of any system.

Use of the Command and Control System

From the time of launch until January 30, 1964, a total of 11,092 command actions were performed with the spacecraft. The command system is a relatively simple one. Three sequential operations must be performed before a command is executed. First, an "enable" tone is transmitted to the spacecraft which applies power to the essential command circuits. Next, a "command" tone is transmitted and removed alternately, resulting in a series of pulses at the command detector output. These pulses are counted and stored but are not effective until an "execute" tone is received by the spacecraft. All tones are transmitted as amplitude modulation on a 148-Mc carrier.

About 99% of all command actions have been successful. A "command action" may be an "enable," "command," or "execute" operation. There is no evidence of any command problem with the spacecraft itself and all difficulties with command can be generally categorized as ground equipment, operator, or station environment related. The apparent problems have occurred during routine operations and have not in any way delayed or compromised any critical control or functional operations on the spacecraft.

Commands may be categorized as two basic types: those that turn on or off various electronic units, and those that actuate the hydrogen peroxide or nitrogen control jets. The axial control jets are offset near the periphery of the spacecraft and thrust parallel to the spin axis; the lateral jets thrust normal to the spin axis and through the center of gravity. The axial jet is operated continuously to change the orbital velocity or inclination of the spacecraft and is pulsed when reorientation of the spin axis is desired. The lateral jets are operated in a pulsed mode and are generally used to change the orbital velocity after the spacecraft spin axis has been reoriented.

The first command transmitted to the spacecraft occurred a few minutes after liftoff on July 26, 1963. This command turned on the transponder transmitter filament and was followed about 4 min later by another command turning on the transponder transmitter high voltage. Communications experiments were then conducted, and shortly before apogee the transponder was commanded off, so that adequate current would be available for firing the apogee motor. Although a command function was available for firing the apogee motor, a timer was also provided, and it was the timer that actually ignited the motor. Subsequent commands were used both to control the attitude and location of the spacecraft and to

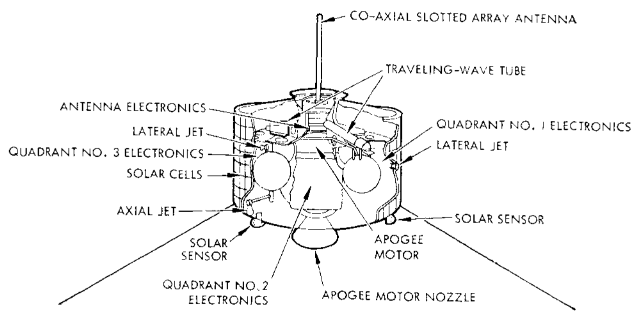

Fig. 1 Cutaway view of SYNCOM spacecraft.

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Table 1 Propellent utilization and velocity corrections for SYNCOM 2

Maneuver	Fluid used	Weight, lb	Δv, fps[a]
Apogee motor firing	JPL 540	60.3	4712.0
Axial jet correction	H_2O_2	1.8	109.8
Reorientation	H_2O_2	0.4	30.0
1st correction	H_2O_2	0.91	37.5
2nd correction	N_2	0.48	13.0
3rd correction	N_2	0.50	14.0
4th correction	N_2	0.048	1.3
Attitude "touchup"	N_2	0.058	1.5
5th correction	H_2O_2	0.063	2.8
Changes in H_2O_2 and N_2 supplies:			
Initially available	H_2O_2	4.9 at 190 psi	...
	N_2	1.82 at 2500 psi	
Remaining 2/27/64	H_2O_2	1.7 at 86 psi	...
	N_2	0.3 at 350 psi	

[a] Derived from preliminary orbit elements.

switch the units of the communications and telemetry systems on and off.

Orbital Maneuvers

The Thor-Delta booster vehicle placed SYNCOM 2 in a near-nominal transfer orbit with a velocity error of only 30 fps. The resulting inclination and eccentricity were 33.14° and 0.73218, respectively. Flight parameters were initially determined at the Goddard Space Flight Center from range, range rate, azimuth, elevation, and Minitrack direction cosine data collected at Lagos, Nigeria, and Johannesburg, South Africa.

The first of the control maneuvers took place as the spacecraft reached the apogee of the transfer orbit and the rocket motor fired, injecting SYNCOM into a nearly synchronous orbit. Table 1 summarizes all control maneuvers and propellent utilization of SYNCOM 2 during the first 7 months of operation. The 4712 fps velocity increment of the apogee motor was 0.3% above nominal and actually improved the orbit. At this point the spacecraft velocity was about 68 fps low, resulting in an eastward drift of 7.03 deg/orbit. The second control correction, therefore, was made using the hydrogen peroxide axial jet in a continuous mode to achieve a velocity increase of 109.8 fps which started the spacecraft drifting 4.53 deg/orbit westward as desired.

The reorientation maneuver was accomplished with a total of 350 pulses of the axial jet, each occurring throughout a 60° sector of the spin cycle. The average torque precessed the spin axis about 82°, bringing the communications antenna nearly normal to the orbital plane. In this attitude the antenna beam continually illuminated the earth, so that communications experiments could take place 24 hr a day.

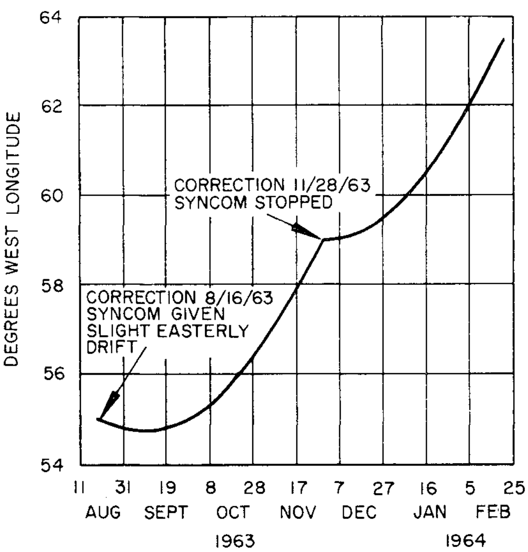

Fig. 2 Equatorial crossings on ascending node.

The sequence of four velocity corrections shown, in Table 1, utilizing the hydrogen peroxide and nitrogen control systems were made with the lateral jets. The attitude "touchup" maneuver put the spin axis within one degree of the normal to the orbital plane. Closer control in attitude is not needed in this application. All control modes had now been exercised successfully and the final orbit was inclined 33.05° with the equatorial crossing at 55° West longitude. Eccentricity of the orbit was approximately 0.00031 and drift of the spacecraft was to the East at 0.04 deg/orbit.

Between August 15 and November 28, 1963, no velocity corrections were made. Acted on by the perturbative forces, resulting from triaxiality of the earth and the additional effect of the sun and moon, the satellite drifted first eastward to about 54.76° West longitude where it reversed direction (about September 10), and then drifted to approximately 59° West longitude by November 28. At that time a correction was made with a train of 65 pulses of the hydrogen peroxide jet to effect the 2.8 fps velocity change that brought the westward drift to a virtual halt and at the same time corrected the eccentricity of the orbit to 0.00005. As of the first of March 1964, no further orbital control was needed with SYNCOM 2. Figure 2 illustrates the longitude of the satellite as it crossed the equator on the ascending node of its inclined orbit.

The experience gained with this early synchronous satellite highlights several important features: 1) Hydrogen peroxide control systems show excellent promise for extended operational use in space, 2) adequate control is achievable with the SYNCOM pulsejet type of control system and spin stabilization in order accurately to position a satellite anywhere around the equatorial plane of the earth with any desired spin axis attitude, 3) less than 10 fps velocity control is adequate to maintain synchronism for one year, and 4) corrections to the spin axis are estimated to be less than 2 deg/year. For the truly stationary orbit that is equatorial and synchronous, an estimated 176 fps/yr is required to hold the satellite in the equatorial plane.

Communications Experiments

Since the time of launch, communications experiments have been conducted almost daily between the spacecraft and one or more of the ground stations. The preparation, execution, and evaluation of the experiments is the responsibility of the U. S. Army Satellite Communications Agency (USASCA) at Fort Monmouth, N. J. Four Army ground stations and a shipboard terminal are used. The two largest stations have parabolic antennas 60 ft in diameter and are located at Camp Roberts, Calif. and Fort Dix, N. J., and two smaller mobile stations are equipped with antennas 30 ft in diameter and are located at Lakehurst, N. J. and Clark Field near Manila in the Philippines. The *USNS Kingsport* is equipped with a 30-ft antenna and operates both at sea and in foreign ports. All of these stations are capable of transmitting several kilowatts of power at 7363 Mc and of receiving both spacecraft communications signals at 1815 Mc and a beacon signal at 1820 Mc.

The spacecraft transmitting antenna pattern is shown in Fig. 3. The pattern is symmetrical about the spin axis; and the main lobe is wide enough to encompass the earth at all times. As of March 1964, over 2000 hr of communications time have been logged using SYNCOM 2, and several thousand communications experiments have been performed. The resulting data are being evaluated by the U. S. Army Satellite Communications Agency. Initial results indicate that the performance of the over-all SYNCOM 2 system is in good agreement with predictions and theoretical results.

Most of the communications experiments that have been conducted consist of three basic classes: voice, teletype, and facsimile. Experiments are conducted in one of several "modems," a term that describes the maximum frequency deviation and the feedback status of the receiver. The various modems are summarized in Table 2.

High-quality voice signals have been received by all stations and signal-to-noise ratios up to 40 db have been reported. High-quality photographs are transmitted by facsimile with a scan period of about 5 min. Direct voice communications have been conducted between stations in the United States and the *USNS Kingsport* as far East as Beirut, Lebanon. The *USNS Kingsport* has also demonstrated that its narrow-beam antennas can be used successfully, while the ship is under way at sea, for voice communications with other stations thousands of miles away.

Over 1000 individual voice conversations have been conducted via the spacecraft in orbit. In addition to confirming the high quality of the resulting voice signals, these experiments have demonstrated that the delay time, caused by the distance that the radio signals must travel via the satellite, does not interfere with normal voice conversation and is generally not noticed by the two speakers. Special tests have been conducted in which voice communications have been received using parabolic antennas as small as 10 ft in diameter, plus a low-noise temperature-parametric amplifier. Because the synchronous orbit of SYNCOM 2 results in low angular rates of the azimuth and elevation angles, the smaller-diameter antennas require only hand tracking for satisfactory communications.

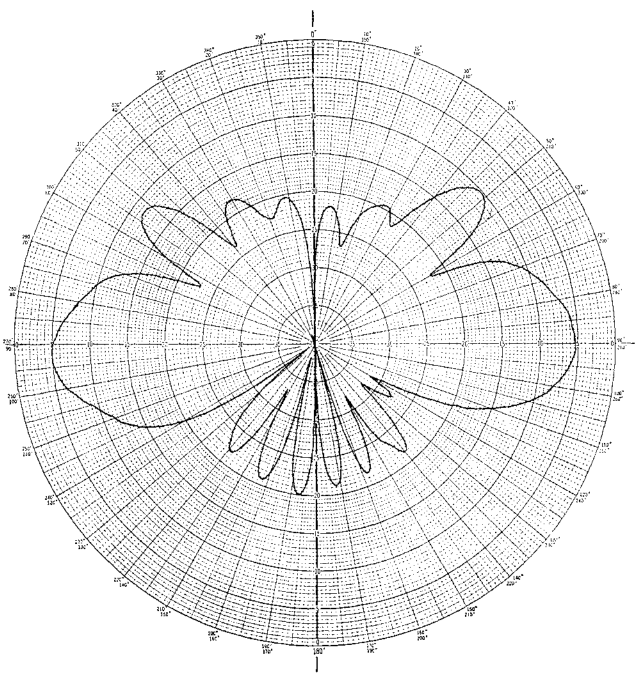

Fig. 3 SYNCOM transmitting antenna pattern.

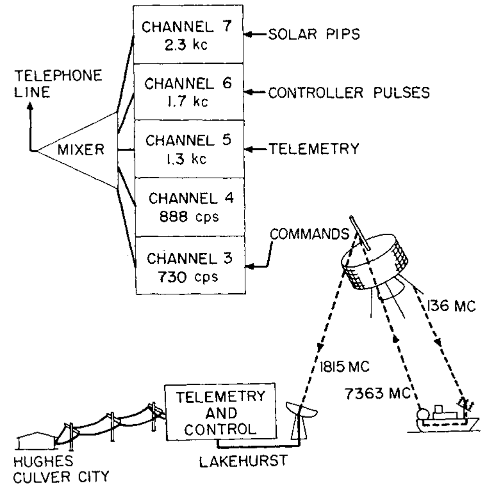

Fig. 4 Real-time data relay experiment.

Commercial television has been transmitted via SYNCOM 2. Although the spacecraft was not designed for this application and the intermediate frequency (i.f.) bandwidth is low for television applications, the results were generally satisfactory. SYNCOM *C* will incorporate a wider bandwidth i.f. in order to improve television transmission.

The feasibility of relaying data via a system consisting of both SYNCOM 2 and commercial land telephone lines was demonstrated while the *USNS Kingsport* was under way in the Mediterranean Sea. The operation is shown schematically in Fig. 4. Real-time telemetry data were transmitted from the satellite to the ship. These data were then transmitted over the communications system back to the spacecraft and reradiated to the Lakehurst, N. J. ground station. Here the telemetry signals were demodulated and transmitted by a commercial telephone line to Culver City, Calif. Several other data signals were transmitted simultaneously over the telephone line, as indicated in Fig. 4. At Culver City, the data were recorded on strip charts and eventually compared with the data received by the ship. The over-all loss in quality was slight, as shown in Fig. 5.

Solar Cell and Battery Performance

The basic power supply for SYNCOM 2 consists of solar cells and a rechargeable nickel-cadmium battery. The solar array is composed of 768 silicon P-N solar cell modules covered with 0.006-in.-thick glass cover-slides. Two nickel-cadmium batteries, each consisting of 22 hermetically sealed cells, supplied power when the satellite was not illuminated during the boost period and during eclipses. The batteries also supply energy for pulse loads, e.g., for firing the apogee motor and the jet solenoids.

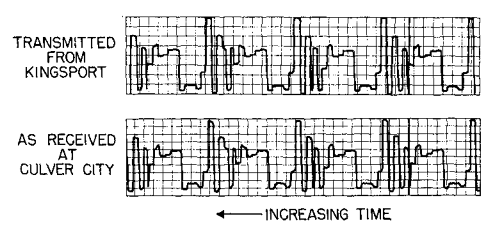

Fig. 5 Telemetry strip charts recorded aboard *USNS Kingsport* in Mediterranean Sea and at Culver City, Calif.

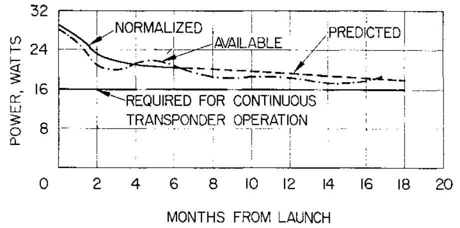

Fig. 6 Measured and predicted values of solar power output.

The measured and predicted values of solar power output are shown in Fig. 6. The predicted values apply to the period that was in the future at the time of this report. The normalized curve indicates the power output based on constant distance to the sun, with the sun's rays perpendicular to the spin axis; hence, it neglects the seasonal cyclic variations. The lower broken curve shows the actual power available, including seasonal variations due to the 21° inclination of the spin axis with the equatorial plane. It is evident that there has been a significant decrease in solar power output since launch, which is attributed to two factors: 1) normal degradation caused by expected radiation, and 2) unexpected degradation caused by solar flare activity.

Although 1963 was regarded as being in a period of minimum solar flare activity, one group of sunspots appeared twice after SYNCOM 2 was launched. The first period reached a peak on August 19 and the second on September 16. It appears that some solar cell damage resulted from the electron flux and subsequently generated x rays and gamma rays. The extent of such damage is difficult to assess, since no radiation measuring devices were carried.

As indicated in Fig. 6, about 16 w is required for continuous operation of a transponder and the command receivers, thereby permitting 24-hr/day communications via the spacecraft. This power level may be used to define the useful life of SYNCOM 2, and it appears that this may exceed 18 months. When 16 w are no longer available continuously, the solar cell voltage will have dropped so low that battery charging will proceed at a very low rate. Therefore, periods of battery operation of the electronics must be spaced by rather long intervals.

The batteries were charged to their full capacity of 34 w-hr before launch and had to support only an 8.5-w telemetry and command receiver load for 3 min between liftoff and removal of the Delta nose fairing. The condition of the batteries is checked occasionally by turning on a sufficient number of electronic units to discharge the batteries to a low level. The units causing the excessive current drain are then turned off and the battery voltage is monitored on the telemetry system. To date (March 1964) there has been no indication of any degradation in battery performance.

During two periods each year, eclipsing occurs (i.e., when spacecraft enters the earth's shadow for a short period each day). These shadow periods are shown in Fig. 7. The

Table 2 Summary of modem characteristics

Modem[a]	Maximum carrier deviation, kc	Baseband frequency, kc
N-N/FM	4	4
W-N/FM	40	4
W-N/FM-FB	40	4
W-W/FM	50	50
W-M/FM-FB	50	20
W-M/FM	50	20
M-M/FM	20	20

[a] M is medium, W is wide, N is narrow, FM is frequency modulated, FB is with feedback.

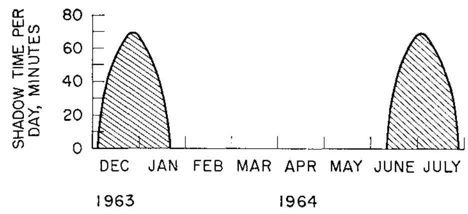

Fig. 7 SYNCOM 2 shadow periods.

maximum shadow periods occurred near the end of December 1963 and lasted about 72 min. Spacecraft ambient temperature is plotted as a function of time in Fig. 8 before, during, and after the eclipse period on December 29, 1963. The transponder was turned off about an hour before entering the shadow. Only the telemetry system and command receivers were on. Note that the spacecraft ambient temperature was about 66°F prior to the eclipse and fell to a minimum of about 25°F during the eclipse period of 72 min. Battery and bus voltages are also plotted. The sharp spike on the bus voltage curve is caused by the low solar cell temperature, and thus efficiency is increased when the spacecraft first enters the sunlight. The solar cell temperature rapidly rises to the final ambient temperature, and the bus voltage drops accordingly. During the eclipse, all power is provided by the batteries, which discharge as indicated. The bus voltage is maintained by the batteries during this period.

Modifications Planned to SYNCOM *C*

Launching of the third SYNCOM spacecraft, designated SYNCOM *C* until launch and thereafter as SYNCOM 3, is planned for the second quarter of 1964.

During the early part of the year, this spacecraft received several modifications as a consequence of SYNCOM 2 experience. N-on-P solar cells with 12-mil fuzed silica covers replaced the more radiation sensitive P-on-N solar cells with their 6-mil glass covers. A redundant hydrogen peroxide system replaced the high-pressure nitrogen system to gain 250 fps in orbital control capability. The standby battery and apogee motor timer were deleted as unnecessary in the next launch operation. The transponder that contained two 500-kc bandwidth i.f. sections was modified to have a 10-Mc i.f. bandwidth, in order to enhance television transmission through the spacecraft. The remaining 5-Mc-bandwidth i.f. transponder was not modified.

These spacecraft improvements, along with the availability of a Thrust Augmented Delta (TAD), enable the establishment of the satellite in a stationary orbit over the Pacific Ocean. A 38° yaw maneuver by the second stage of the TAD is expected to remove some of the inclination following third-stage burnout. A spacecraft attitude adjustment near second apogee is planned, so that with the spacecraft rocket motor firing at third apogee and with an additional 75-fps velocity increment from the hydrogen peroxide system, a synchronous, circular, equatorial (station-

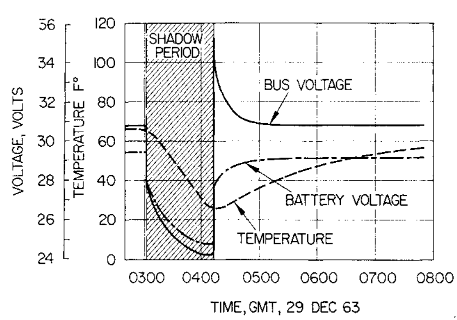

Fig. 8 Spacecraft temperature, bus voltage, and battery voltage as functions of time during eclipse period.

ary) orbit may be achieved. Since the total energy for these orbital maneuvers is marginal, it can be completely successful only if booster deviations do not exceed about one sigma, otherwise some inclination of the orbit must be accepted after placing the satellite on station (about 175° West longitude) and synchronizing its velocity with the earth's rotation.

Conclusions

The SYNCOM satellite program has established the feasibility and advantages of the 24-hr spacecraft as a communications relay. Further applications for meteorological, navigational, and scientific purposes seem likely. Future systems will incorporate design features proved in this program.

Immediate improvements that may be expected in follow-on systems to SYNCOM include increased solar power, wider-bandwidth transponders, higher radiated power from the spacecraft transmitters, higher antenna gains, and lighter, more efficient subsystems with longer life expectancy. Design goals of three years, service are reasonable in today's development. Within a decade, a satellite life of ten years is very probable.

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Results of Studies on a Twin-Gyro Attitude-Control System for Space Vehicles

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The system studied here consists of a twin-gyro controller for each of three orthogonal axes of a space vehicle. With a twin-gyro controller about each axis, the cross coupling generally associated with systems using a single gyro about each axis is eliminated. The elimination of this cross coupling allows the use of large gimbal angles, so that a large portion of the momentum stored in the gyros is available for transfer to vehicle. The control system had rapid response and good damping characteristics. In an automatic closed-loop mode the control system was able to maintain the attitude of the simulator to within 1 sec of arc about all axes. In a manually operated mode the pilot was able to maintain attitude to within 5 sec of arc.

Nomenclature

H = total angular momentum about momentum-exchange axis
h = angular momentum of one gyro
K_1, K_2, K_3 = gain constants
θ_c = angular position of gyros with respect to spin-reference axis
φ, θ, ψ = attitude angles about roll, pitch, and yaw axes of vehicle
τ = time constant

Introduction

DURING the midcourse phase of manned space flights, while navigational sightings are being made, the attitude of the vehicle will have to be stabilized to some extent. The attitude limits and rate requirements of the stabilization system will depend on the navigational sighting equipment and the accuracy required. It may be desirable to stabilize the attitude of the vehicle to within a few seconds of arc to insure the accuracy needed for mission accomplishment.

One attractive approach to vehicle attitude control is the use of twin-gyro controllers as torque sources. With a twin-gyro controller for each axis, the gyroscopic cross coupling inherent in a single-gyro system is eliminated, thereby allowing large gimbal angle deflections, so that a major portion of the momentum stored in the gyros is available for transfer to the vehicle. The elimination of cross coupling also permits the use of an independent control system for each axis. This facilitates the introduction of a pilot into the control loop.

An investigation has been completed at NASA Ames Research Center on the attitude stabilization of a large space vehicle that uses twin gyros as torque sources. Two control systems—automatic closed-loop and pilot-operated—have been investigated. The automatic system was capable of maintaining attitude stabilization to within 1 sec of arc. The pilot-operated system was capable of attitude stabilization to 5 sec of arc.

Theory of Twin-Gyro Controllers

The construction of the twin-gyro controllers was based on the study reported in Ref. 1. Synchros were used as gimbal position sensors, and geared servomotors were used to position the gimbals.

A twin-gyro controller is shown schematically in Fig. 1. The two gyros are shown supported by a framework rigidly attached to a vehicle. With no input signal, the gyros have their angular momentum vectors aligned along the spin reference axis but in opposite directions. For a given input signal, the gyros are forced to turn through equal and opposite angles $\pm\theta_c$. The components of momentum along the momentum-exchange axis add directly. The components of momentum along the other two axes cancel. The component of momentum about the momentum-exchange axis is $H = 2h \sin\theta_c$, where H is the total momentum about the momentum exchange axis and h is the angular momentum of each gyro. The torque applied to the vehicle, through the framework, is the time-rate change of momentum $2h\dot{\theta}_c \cos\theta_c$.

Each twin-gyro controller had an angular momentum of about 110×10^6 g-cm²/sec or about 8 slug-ft²/sec. The servomotors were capable of a maximum gimbal angle rate of change $\dot{\theta}_c$ of about 1 rad/sec. The resulting torque to the

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