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EXTENDING SYNCOM 3'S ORBITAL LIFE OVER THE PACIFIC

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Summary

Syncom 3, launched in August 1964, was the first satellite to be maneuvered to a near-stationary orbit. It is presently functioning as an essential communication link between Hawaii and the Far East. As long as the satellite remains within mutual visibility of these areas, this link will continue to exist. Ironically, the by-product of an unwanted process, namely, gas resulting from decomposition of the propellant (hydrogen peroxide) which was originally intended to provide orbital control, is now being used to maintain this link. If the satellite orbit were not controllable, Syncom 3 would drift out of the mutual visibility longitude band as a result of forces exerted by the earth's triaxiality. The unstable equilibrium longitude in the Pacific, computed to be at 162.4°E , lies within this band.¹ Near this point, the control velocity requirements are small, so that minimal control capability, such as is available from the gas, could extend Syncom 3's orbital life for as much as 10 years. This is unlikely, however, because of the degraded condition of the batteries which are essential for operation of the control jets. The satellite on its present drift trajectory should remain visible from Hawaii until early 1969.

Longitudinal control of Syncom 3 in the vicinity of the Pacific equilibrium longitude has now been accomplished with gas for approximately 1.5 years. The specific impulse observed is approximately 57.1 seconds. The mass flow rates observed have resulted in velocity increments of about 0.005 fps per pulse. Such high resolution is required to maintain the satellite position close to but west of the equilibrium longitude. This constraint is based on the increased visibility time for westerly drift in case of complete loss or depletion of control capability. Since the batteries are weak and gas leaks are to be expected in a system not originally designed for use of gas, such a constraint is reasonable.

Orbital Analyses

A satellite in a perfectly circular equatorial orbit with an orbital period exactly equal to the earth's rotational period appears perfectly stationary to an observer on the earth. However, the presence of various perturbations on the satellite orbit tends to introduce a motion of the satellite ground track. As the orbit acquires small eccentricity and inclination, the ground track becomes a small ellipse centered above the equator with a maximum north-south excursion equal to the orbital inclination and a

maximum east-west angular distance of twice the eccentricity.

Perturbations in the orbital period cause this ellipse to drift. The perturbations affecting the orbit of a nearly stationary satellite are solar and lunar gravitational attractions, the earth's oblateness, solar radiation pressure, and the earth's triaxiality. The last is the most significant long-term effect responsible for the satellite's drift.

The earth's triaxiality is used here to refer to the perturbation caused by all the longitude-dependent terms in the earth's potential expansion. Since the subsatellite longitude of a nearly stationary satellite changes very slowly, these terms produce a nearly constant tangential acceleration. An expression for this acceleration is

$$a_{\theta} = 6g(R_e/R)^4 J_{22} \sin(2\lambda - 2\lambda'_{22}) \\ + \text{higher order terms, ft/sec}^2 \quad (1)$$

where λ is the satellite longitude, J_{22} and λ'_{22} are constants in the earth's potential,¹ g is the acceleration of gravity at the earth's surface, R_e is the earth radius, and R is the satellite orbital radius. Since the J_{22} term is an order of magnitude larger than any higher order term, the tangential acceleration may be approximated by an expression of the form

$$a_{\theta} \doteq 6g(R_e/R)^4 J'_{22} \sin(2\lambda - 2\lambda'_{22}) \text{ ft/sec}^2 \quad (2)$$

where different pairs of J'_{22} and λ'_{22} are used in different longitude bands to include the changing effects of the higher order terms.

Since the tangential acceleration is related to the longitudinal drift acceleration by a constant, Equation 2 indicates that for a stationary satellite there are two stable equilibrium longitudes, with unstable equilibrium longitudes located 90° from the stable ones. Equation 2 permits both an oscillatory solution (in which the satellite will oscillate in a pendulum-like manner about one of the stable points) and a non-oscillatory solution (in which the satellite ground track will drift completely around the earth). Both solutions are illustrated in the family of drift trajectories shown in Figure 1. Note the bunching up of the constant time lines near the 90° relative longitude. This condition indicates

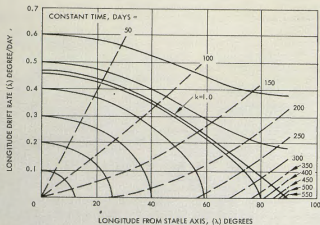


Figure 1. Motion Due to Triaxiality

the large amount of time that a satellite will spend in the vicinity of an unstable equilibrium point.

The Syncom 3 satellite has been situated at longitudes near the unstable equilibrium point which is located over the Pacific Ocean. An accurate estimate of the location of this equilibrium point was obtained from Syncom 3 tracking data during a 7-month period beginning November 1965 when the satellite drifted freely from 188° to 195°W longitude.¹ This analysis produced an estimate of the Pacific equilibrium longitude as 197.6°W, indicating that this value of λ'_{22} , along with an effective J_{22} of 2.2×10^{-6} , should be used with Equation 1 in this longitude band. Later orbital data taken for the Syncom 3 satellite in a band from 3° to 5°W of the Pacific equilibrium point indicates that values for λ'_{22} of 197.6° and J_{22} of 1.8×10^{-6} are appropriate for this band.

For a satellite near the unstable equilibrium point, approximate oscillatory solutions to Equation 2 for longitude λ and drift rate $\dot{\lambda}$ are

$$\lambda(t) = (\lambda_m - \lambda'_{22}) \cosh \left[\left(\frac{6A'_{22}}{R} \right)^{1/2} (t - t_m) \right] + \lambda'_{22}, \text{ radians} \quad (3)$$

$$\dot{\lambda}(t) = \left(\frac{6A'_{22}}{R} \right)^{1/2} (\lambda_m - \lambda'_{22}) \sinh \left[\left(\frac{6A'_{22}}{R} \right)^{1/2} (t - t_m) \right], \text{ rad/sec} \quad (4)$$

where λ_m is the longitude corresponding to zero drift rate (turnaround longitude), t_m is the corresponding turnaround time, and $A'_{22} = 6g(R_e/R)^4 J_{22}$. Figure 2 shows a plot of satellite motion corresponding to these solutions. It may be seen that a satellite with a suitable initial drift in a direction opposite to that of its acceleration will slow down to zero drift, then reverse its drift and accelerate toward the stable equilibrium point. The amount of time spent in a given longitude band may be maximized by

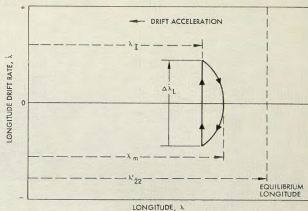


Figure 2. Limit Cycle in Band ($\lambda_m - \lambda_1$)

choosing the initial longitude at one end of the band and the initial drift rate such that the turnaround point is at the other end of the band. After reversing drift direction, the satellite will, in an equal amount of time, return to the initial longitude with a drift rate of equal magnitude and opposite direction to the initial drift. If the satellite is to remain in the desired longitude band, the drift rate must then be reversed to permit the cycle to repeat. This optimal cycle is depicted in Figure 2. Thus, to keep Syncom 3 in any desired longitude band, it is necessary to be able to change the satellite drift rate at designated intervals.

The satellite drift rate is changed instantaneously by the application of a tangential velocity impulse that changes the length of the orbit's semimajor axes, hence changing the orbital period. A tangential velocity increment ΔV is related to the change in drift rate it produces, $\Delta \dot{\lambda}$, by

$$|\Delta \dot{\lambda}| = \frac{3}{R} |\Delta V|, \quad \text{rad/sec} \quad (5)$$

To compensate for the perturbing triaxial acceleration and maintain a limit cycle such as illustrated in Figure 2, the drift reversal magnitude is

$$|\Delta \dot{\lambda}|_L = 2 \left(\frac{6A'_{22}}{R} \right)^{1/2} \left[(\lambda_1 - \lambda'_{22})^2 - (\lambda_m - \lambda'_{22})^2 \right]^{1/2}, \quad \text{rad/sec} \quad (6)$$

The time between corrections is given by

$$T_L = 2 \left(\frac{6A'_{22}}{R} \right)^{-1/2} \cosh^{-1} \left[\frac{(\lambda_1 - \lambda'_{22})}{(\lambda_m - \lambda'_{22})} \right], \text{ seconds} \quad (7)$$

For $J_{22}^1 = 1.8 \times 10^{-6}$,

$$|\Delta V|_L = 0.142 \left[(\lambda_I - \lambda_{22}^1)^2 - (\lambda_m - \lambda_{22}^1)^2 \right]^{1/2}, \text{ fps} \quad (8)$$

$$T_L = 261.6 \cosh^{-1} \left[\frac{(\lambda_I - \lambda_{22}^1)}{(\lambda_m - \lambda_{22}^1)} \right], \text{ sidereal days} \quad (9)$$

The velocity requirements for maintaining the limit cycle in the vicinity of the unstable longitude are then

$$\text{Vel. Req.} = 0.2 \frac{\left[(\lambda_I - \lambda_{22}^1)^2 - (\lambda_m - \lambda_{22}^1)^2 \right]^{1/2}}{\cosh^{-1} \left[\frac{(\lambda_I - \lambda_{22}^1)}{(\lambda_m - \lambda_{22}^1)} \right]}, \text{ ft/sec/yr} \quad (10)$$

Control System

Control Concept

Syncom 3 is a spin-stabilized spacecraft with propulsion jets that can be commanded to provide thrust either parallel or perpendicular to the spin axis. The jet-producing thrust parallel to the spin axis also provides torque normal to this axis since it is physically offset from the spin axis. This torque may be used to precess the spin axis but only if a time average component exists in the spatial direction in which the axis is to be moved. The jet-producing thrust perpendicular to the spin axis is aligned through the spacecraft center of gravity. This thrust may be used to produce acceleration but again only if there is a time average component in the spatial direction of the desired net acceleration.

The net effect of precession or acceleration is achieved by operating the control jets over a fixed portion of each spin cycle relative to an external reference. In the Syncom system, this external reference is provided by the sun. Command pulses are sent in synchronism with the spin in real time, with the proper time delay relative to the primary solar sensor pulse, and for a duration corresponding to 60 degrees of spin.

These functions are performed using a rotating mechanical contactor device driven synchronously with the spin, lock being maintained by an electronic control loop such that the primary solar sensor pulses are tracked. This device is known as the synchronous controller drum unit. A dial positions the command contacts around the periphery of the drum. Its reading is equal to the number of degrees of spin from the time of reception of the primary solar sensor pulse to the start of the command pulse. The dial setting is computed for the desired spatial direction of thrust or torque relative to that of the sun, taking account of the body-fixed

geometry of the control jets relative to the sun sensor beam plane, the location of the pulse centroid relative to initiation of the pulse, and the two-way propagation delay.

Either the axial or the radial jet could also be operated in continuous mode. Since the axial jet thrusts parallel to the spin axis, it may be operated over a number of spin cycles to produce a net acceleration along this axis.

Control Propulsion

Syncom 3 was designed with two independent control systems. Each system contains its own radial and axial control jets. Initially, four spherical tanks, two per system for static balance, were loaded with hydrogen peroxide for propulsion. About 60 percent of the volume of the tanks was occupied with this fluid at 90 percent concentration and the remainder with nitrogen at about 210 psia. The spin provides a pressure head, and as fuel is depleted the tank pressure falls off.

Because of impurities in the storage tanks, the peroxide decomposes with time. Were it not for this decomposition, the thrust would decrease with fuel usage, mainly due to the dependence of mass flow rate on tank pressure. However, concomitant evolution of oxygen causes the tank pressure to increase during the period when fuel is not utilized for maneuvers; if the pressure increases to approximately 250 psia, a relief valve vents the excess pressure.

Although the production of oxygen tends to increase the flow rate as pressure rises, a more serious effect on thrust is decreased propellant specific impulse caused by reduced peroxide concentration. The latter decreases rapidly as the concentration approaches 60 percent, and effectively zero thrust can be realized from the peroxide below this level.

The engines employ solenoid valves which open upon command to permit the flow of peroxide from tank to chamber. These valves are opened by an electromagnetically produced force that compresses the spring which normally maintains valve closure. When compressed, the spring is uncoupled from the valve so that the latter may be pushed open by the pressure from within the tank. This method makes proper valve openings vulnerable to low tank pressures. Other conditions that could impede nominal flow are 1) formation of chemical adhesives around the valve seat and 2) degradation of the batteries that provide the current through the solenoid.

Peroxide Depletion

A rise in tank pressure is produced by the evolution of oxygen associated with the decomposing hydrogen peroxide. This decomposition is an indication of chemical uncleanness in the storage tanks, a fact of life which should be kept minimal. Both control systems in Syncom 3 were beset by this problem to an alarming degree (Syncom 2 was almost free from this problem) almost from the time the spacecraft was injected into stationary orbit. An average effective pressure rise rate of approximately 1.5 psia per day

was calculated. This effect was to provide a problem throughout the useful life of the propellant.

System 2

The problem of increasing tank pressure in what is known as System 2 first became acute in late 1964 when it was noted that the pressure relief valve did not seem to open. The tank pressure had reached 285 psia in the relatively short time since launch. The pressure relief valve was supposed to open at the design pressure of approximately 250 psia. It then became necessary to dump fuel to maintain the pressure below about 300 psia. Higher pressures were believed detrimental to the entire spacecraft.

The first fuel dump maneuver occurred on 12 December 1964. The weight of peroxide used for maneuvers prior to this date was 2.38 pounds, leaving 2.54 pounds remaining. Fuel dumps were accomplished using the axial engine in continuous mode with an attempt to drive inclination in a direction opposite to the effect of sun and moon perturbations. In so doing, these maneuvers were not entirely wasteful of propellant. Table 1 illustrates the history of maneuvers using System 2 from this date to the time the peroxide was depleted. Those maneuvers marked by an asterisk were primarily intended to reduce the tank pressure by fuel expulsion, while the others were performed to achieve either orbit or attitude control. On 16 July 1965, the final peroxide was dumped from System 2. A pressure drop much larger than expected indicated that this had occurred.

TABLE 1. SYSTEM 2 PEROXIDE DEPLETION

Maneuver Date	Pressure, psi		Fuel, pounds	
	Initial	Final	Initial	Final
12 December 1964*	288	280	2.54	2.37
29 December 1964*	288	247	2.37	1.40
14 January 1965	264	260	1.40	1.30
18 January 1965	264	260	1.30	1.19
4 March 1965*	295	291	1.19	1.09
18 March 1965*	294	288	1.09	0.93
26 March 1965	295	292	0.93	0.85
29 March 1965*	293	284	0.85	0.61
31 March 1965	284	280	0.61	0.52
29 April 1965	296	295	0.52	0.48
26 May 1965*	303	295	0.48	0.27
30 June 1965	305	301	0.27	0.15
16 July 1965*	304	273	0.15	0

System 1

In early January 1965, it was noted that the tank pressure in what is known as System 1 was remaining constant at about 270 psia after having

gone through a prolonged rise since its last usage on 2 October 1964. It was concluded that this was due to opening of the relief valve although concomitant telemetry limiting forced the use of 40 percent of the peroxide in this system to ascertain this fact. The latter was accomplished on 15 January 1965 by operating the radial jet continuously until the tank pressure fell to a desired level. Given the known parameters, the actual premaneuver pressure was computed and compared with both the telemetry limited pressure and the extrapolated pressure based on known rise rate. Agreement was found with the former, indicating that venting had occurred. Since the usage of fuel tends to aggravate the decomposition rate because of increased tank surface-to-volume ratio, this experiment was undoubtedly costly to the useful life of the peroxide in System 1.

In September 1965, it was decided to move the subsatellite longitude to the vicinity of the Pacific equilibrium longitude. This recommendation was based on the replacement of Camp Roberts by Hawaii as the eastern terminal of the link to the Far East. The effect of this move was to extend the western bound of the mutual visibility longitude interval to encompass the Pacific equilibrium longitude. In the vicinity of this point, the velocity requirements for maintaining satellite longitudinal position are small. Thus, for a given control availability, the satellite position may be maintained for a longer period of time, giving rise to extended useful life of this link to the Far East. Further, an estimate in August 1965 of the peroxide concentration in System 1 indicated that, at best, the concentration would have fallen to 60 percent by March 1966. Since the peroxide is probably not usable below this level, the control capability would then be left to the gas, provided it did not leak out.

Three velocity corrections (on 5, 19, and 29 October 1965) were performed using System 1. The target was a drift trajectory such that the satellite would arrive at the Pacific equilibrium point with zero drift rate starting from an initial longitude of approximately 174°E. Prior to the first maneuver, it was expected that an additional maneuver(s) would be required for recalibration since System 1 had not been operated in pulsed mode since 2 October 1964. Table 2 illustrates the actual velocity increments achieved in the sequence of three maneuvers and compares them with those that would have been achieved with the fresh system as it performed in early Fall 1964.

TABLE 2. SYSTEM 1 PEROXIDE PERFORMANCE

Maneuver Date	Number of Pulses	Velocity Increment		Ratio
		Present	Past	
5 October 1965	32	0.84	1.76	0.48
19 October 1965	30	0.60	1.60	0.38
29 October 1965	13	0.15	0.69	0.23

The attenuated performance indicated for all three maneuvers resulted from the decreased peroxide concentration arising from decomposition over the long period of time since the system was last used. The rate of change of performance from the first through the third correction is an indication that the concentration was near the unusable level at this time, since near this level performance is much more sensitive to decreased concentration. This effect is amplified with fuel usage because the surface-to-volume ratio increases, thereby increasing the decomposition rate. An estimate based on results of these maneuvers predicted impotency for the peroxide in System 1 by the end of 1965.

Maneuvering With Gas

On 8 June 1966, it was reported that the westward drift would slow to zero on 15 July at a longitude of 164.85°E. This was short of the 162.4°E Pacific equilibrium longitude, the latter being determined by suitably processing periodic orbit determinations along the drift trajectory which began after the three velocity corrections of October 1965.¹ It was planned that shortly after the drift reversed, a maneuver sequence would be executed to drift the satellite further west on a trajectory such that it would arrive at 162.4°E longitude with zero drift rate. The energy for this maneuver and all subsequent maneuvers would have to come from the trapped gas. The pressures in the control systems had been holding fairly steady during the preceding months at 250 psia for System 2 and 180 psia for System 1. It remained to be seen what sort of control capability could be harnessed from this gas.

Theory²

The theoretical performance of the gas used in conjunction with the Syncom 3 nozzle is derived based on the assumptions that the gas is essentially oxygen, the ratio of specific heats $\gamma = 1.4$, and the flow isentropic. The velocity in the throat of the nozzle in isentropic flow for $\gamma = 1.4$ is

$$a_t = 0.913 a_o \quad (11)$$

The reservoir or tank temperature of the gas is assumed to be 70°F, giving a speed of sound in the reservoir of $a_o = 1116.9$ fps. Thus, $a_t = 1020$ fps.

The density of the gas at the throat is

$$\rho_t = \left(\frac{2}{\gamma+1}\right)^{1/(\gamma-1)} \rho_o = 0.634 \rho_o \quad (12)$$

The density of the gas in the tank ρ_o is

$$\rho_o = 0.00608 P_o \text{ lb/ft}^3 \quad (13)$$

where P_o = tank pressure, psia, so that

$$\rho_t = 0.00385 P_o \text{ lb/ft}^3 \quad (14)$$

The mass flow in the nozzle is

$$\dot{m} = A_t a_t \rho_t \text{ lb/sec} \quad (15)$$

where A_t = cross-sectional area of throat. For Syncom 3, the throat diameter equals 0.122 inch; therefore,

$$\dot{m} = \frac{\pi(0.122)^2}{4(144)} \times 1020 \times 0.00385 P_o = 0.0003195 P_o \text{ lb/sec} \quad (16)$$

The theoretical maximum specific impulse is found from

$$c = g(I_{sp})_{\max} = \left(\frac{2}{\gamma-1}\right)^{1/2} a_o \quad (17)$$

where c = maximum exhaust velocity. The actual specific impulse is smaller due to the finite expansion ratio.

The exhaust velocity is given by

$$V_e = c \left(1 - X(\gamma-1)/\gamma\right)^{1/2} \quad (18)$$

where X , the ratio of exit pressure to supply pressure, is related to the expansion ratio by

$$\frac{1}{\epsilon} = X^{1/\gamma} \left(\frac{\gamma+1}{2}\right)^{1/(\gamma-1)} \left(\frac{\gamma+1}{\gamma-1}\right)^{1/2} \left(1 - X(\gamma-1)/\gamma\right)^{1/2} \quad (19)$$

where $\epsilon = A_e/A_t$ = exit area/throat area, expansion ratio. For Syncom 3, $\epsilon = 17:1$ which, from Equation 19, at $\gamma = 1.4$ gives $X = 3.324 \times 10^{-3}$.

The thrust is

$$F = \frac{\dot{m}}{g} V_e + P_e A_e \quad (20)$$

where P_e = exit pressure. The contribution of $P_e A_e$ to total thrust is only about 2 percent, and hence will be ignored for this computation. Thus, the specific impulse is essentially independent of flow rate:

$$I_{sp} \approx \frac{V_e}{g} = \frac{c \left(1 - X(\gamma-1)/\gamma\right)^{1/2}}{g} \\ = (I_{sp})_{\max} \left(1 - X(\gamma-1)/\gamma\right)^{1/2} \quad (21)$$

From Equation 17, for $\gamma = 1.4$ and $a_o = 1116.9$ fps at 70°F,

$$(I_{sp})_{\max} = 77.6 \text{ seconds} \quad (22)$$

so that

$$I_{sp} \approx 62.4 \text{ seconds} \quad (23)$$

The mass of the gas in the tank is related to the tank pressure by

$$m_0 = 0.000565 P_0 \quad (24)$$

Thus, for pressures of 250 psia and 180 psia for Systems 2 and 1, there existed 0.141 and 0.102 pound of gas, respectively. This total of 0.243 pound represented 6.25 fps of velocity control at 62.4 seconds t_{sp} , spacecraft mass 2.3 slugs, and geometry factor for 60 degrees of spin equal to 0.95.

The slowdown time is given by

$$t_B = 1.77 \ln \frac{P_{0i}}{P_{0f}} \text{ (seconds)} \quad (25)$$

where P_{0i} and P_{0f} are the initial and final tank pressures. For a 60-degree pulse, the duration of the pulse train would be six times the slowdown time. For a typical correction of 0.25 fps, assuming an initial tank pressure of 200 psia, the duration of the pulse train would be about 0.9 second, corresponding to between two and three pulses at a spin speed of about 170 rpm.

As the initial tank pressure decreases, the slowdown time for a given velocity increment increases in accordance with the exponential relation. Consequently, it appears that it would be difficult to achieve small velocity increments accurately until much of the gas had been utilized. Evidently, the relatively large flow rates associated with the Syncom 3 nozzle and its 60-degree pulse width were not designed for accurate small velocity corrections using gas.

Maneuvers With System 2

Because of what appeared to be a serious loss of tank pressure, an emergency maneuver was executed on 15 June 1966 using System 2. The observed pressure had decreased from about 250 to 42 psia just prior to the maneuver. Sixty pulses were committed, which decreased the tank pressure to 7 psia. The mean drift rate was increased from 0.005 to 0.061°W/day at a mean longitude of 165.05°E. This was much larger than that required (approximately 0.023°W/day) to target for stationarity at 162.4°E. The fear of loss of all capability at that time made it desirable to move the satellite to the selected longitude at a more rapid rate.

It was concluded at that time that the loss of pressure was due to a leak. If this were the case, the capability which existed in System 2 was, for all practical purposes, lost. The second maneuver proved this not to be the case.

On 24 August 1966, the Syncom 3 orbit was essentially synchronized. More specifically, the mean satellite drift rate was reduced from 0.052°W/day to 0.007°W/day at a mean longitude of 161.35°E. This correction was performed using System 2. The change in orbital energy observed required a pressure drop of approximately 30 psia. Since the telemetry reported that only 7 psia was left in this system, it was clear that the sensing system associated with

System 2 had malfunctioned. Further, the system had probably not leaked at all before the first maneuver and thus still had control capability available. An estimate of this capability will be presented subsequently.

This maneuver was attempted with System 2 only because an attempt using System 1 failed. Initially, the plan consisted of pulsing the System 1 radial jet for a few pulses in a spatial direction normal to the existing velocity vector prior to executing the actual maneuver. The purpose of this was to cleanse the system of any remaining liquid (the diluted peroxide had not been expelled, and an accurate estimate of the amount remaining was not available) to produce a more predictable flow rate. By firing in the stated direction, the drift rate would be influenced only to the second order. An indicated pressure drop of more than 5 psia on any one pulse train was to serve as a criterion of cleanliness. Several pulse trains were committed without observable pressure reduction. It was concluded that either not enough liquid had been eliminated or the valve would not open. The problem was to be studied before another attempt was made. It was then decided to exhaust the remaining gas from System 2.

Maneuvers With System 1

Between 24 August 1966 and 10 March 1967, the satellite had drifted westward under the influence of the earth's triaxiality. The long drift period without maneuvers was necessary at this time since it was desirable to locate a safe distance from the equilibrium longitude on the west side before attempting further corrections. This was because no definite knowledge as to the accuracy of control using the gas was as yet available. In the event of a complete loss of control, it was undesirable from the standpoint of orbital life from Hawaii to the Far East for the satellite to drift eastward past the equilibrium longitude.

The satellite longitude on 10 March was 158.75°E. A velocity correction intended to reverse the drift was attempted using System 1. For 1 hour prior to this, the repeaters and telemetry were turned off in an attempt to charge the battery. The maneuver produced no orbital change.

On 18 April 1967, the satellite longitude was 157.95°E. Battery charging was performed for a period of 10 hours. A series of five pulse trains were executed. The reductions in tank pressure are itemized in Table 3. The first three pulse trains contained essentially the same number of pulses, yet the indicated pressure drops decreased. The fourth and fifth pulse train showed no pressure change at all. This phenomenon appears to be due to a weak battery; i. e., on the first train, only a fraction of the pulses drew enough current from the battery to produce sufficient force to cause valve opening. These pulses probably existed at the beginning of the train. Ten minutes separated the first train from the second. Since batteries tend to recuperate somewhat after usage, sufficient current could be drawn to cause some pulses from the second train to be effective but a lesser number

TABLE 3. MANEUVER - 18 APRIL 1967
(SYSTEM 1)

Time(Z)	Number of Pulses	Recorded Tank Pressure, psia	
		Initial	Final
18 April 2356	14	150	143
19 April 0006	15	143	139
0016	15	139	137
0022	23	137	137
0030	29	137	137

than for the first train. Finally, the battery returned to a state from which it could not recuperate sufficiently to cause valve opening without being externally charged.

From this theory, it was concluded that more effective pulses could be achieved if the number of pulses or any one pulse train was minimal. This would leave the battery at a more powerful level from which to recuperate for the next pulse train. The philosophy for the next correction then would be to commit as many of these pulse trains as required to achieve the desired system pressure drop. These pulse trains would be separated in time to allow battery recuperation.

The total pressure drop from smoothed data for the 18 April maneuver was 12 psia, from 152 to 140. The results of orbit determination produced a change in mean drift rate from 0.0289°W/day to 0.0112°W/day, corresponding to a velocity increment of 0.165 fps. From these data, the specific impulse of the gas was computed to be 58.9 seconds.

The 18 April maneuver failed to reverse the drift rate although an orbital energy change was achieved. On 17 May 1967, another velocity correction was performed intending to reverse the drift. Battery charging was performed for 13 hours. A series of seven pulse trains were executed with tank pressure changes as indicated in Table 4. The satellite mean longitude was 157.4°E.

The total desired pressure drop of some 40 psia was not achieved since the exercise was cut short because it was necessary to turn on the repeaters. The long pulse train (24 pulses) was committed with the knowledge that it would be the last. After smoothing the pressure data, a change from 140 psia to 121.5 psia was calculated. The results of orbit determination indicated a change in mean drift from 0.021°W/day to 0.005°E/day, corresponding to a velocity increment of 0.243 fps. From these data, the specific impulse of the gas was computed to be 56.3 seconds.

TABLE 4. MANEUVER - 17 MAY 1967
(SYSTEM 1)

Time(Z)	Number of Pulses	Recorded Tank Pressure, psia	
		Initial	Final
17 May 2311	3	138.8	138.5
2320	3	138.5	138.0
2330	7	138.0	136.5
2341	9	136.5	132.5
2350	9	132.5	128.8
18 May 0005	7	128.8	127.0
0020	24	127.0	121.0

A reversal of drift from west to east was attained. However, the resulting small eastward drift would not move the satellite very far east before the triaxial force reversed its drift direction. On 2 June, another velocity correction was performed to augment the eastward drift rate to an extent that the satellite would drift toward the Pacific stationary longitude without overshooting it. System 1 was used as before. Battery charging was performed for 15 hours prior to execution of the maneuver. A series of ten pulse trains were committed, with tank pressure changes given in Table 5. The satellite mean longitude was 157.5°E.

TABLE 5. MANEUVER - 2 JUNE 1967
(SYSTEM 1)

Time(Z)	Number of Pulses	Recorded Tank Pressure, psia	
		Initial	Final
2 June 2200	6	120.5	118.6
2210	6	118.6	118.0
2220	10	118.0	114.6
2245	9	114.6	111.6
2250	9	111.6	108.5
2300	9	108.5	105.6
2310	9	105.6	104.0
2320	9	104.0	102.6
2335	9	102.6	99.5
2350	6	99.5	98.0

Smoothing the data produced a total pressure change of 23 psia, from 121.5 to 98.5 psia. The results of orbit determination indicated that the mean drift rate was altered from 0.00095°W/day to 0.0314°E/day, corresponding to an applied velocity increment of 0.302 fps. From these data, the specific impulse of the gas was computed to be 56.2 seconds.

Results of Maneuvers With Gas

Table 6 summarizes the performance of the gas for the maneuvers discussed. Indicated are the maneuver dates, control system used, tank pressure changes, and theoretical and observed specific impulse and mass flow rates. The actual specific impulse shown for System 2 is derived by averaging the three values observed from the corrections using System 1. Assuming the validity of this quantity, the other starred quantities may be determined.

Important features of the summary are as follows:

- 1) The specific impulses (I_{sp}) derived from results of the three maneuvers using System 1 are consistent and show good agreement with the theory.
- 2) The observed mass flow rates (\dot{m} , lb/sec) are approximately an order of magnitude smaller than predicted, indicating a significant departure from isentropic conditions. Physically, this is probably because of dissipative forces at the junction of the valve seat and the tank resulting from unclean valve openings. Since specific impulse is essentially independent of mass flow rate, this has little effect on the agreement noted above for I_{sp} .
- 3) The final pressures noted in Table 6 represent a potential velocity correction capability of 1.31 fps in System 1 and 2.38 fps in System 2.

The extension of Syncom 3's orbital life in the Pacific assumes the requirement for mutual visibility from both the Far East and Hawaii. This visibility band extends from about 127°E to 174°E longitude. The Pacific equilibrium longitude at 162.4°E lies within this band. Since the time that gas became the sole source of Syncom 3's control capability, the aim has been to stationkeep the satellite's longitude west of and as near to the equilibrium longitude as possible without risking drift to the east. The latter constraint is based on the increased visibility time for westerly drift in case of complete loss or depletion of this control capability.

Figure 3 illustrates the history of the drift trajectories for Syncom 3 since the first maneuver with gas on 15 June 1966. The plot of drift rate versus longitude shows the maneuvers as step changes in the drift rate at constant longitude. Positive values of the drift rate indicate westward movement. The arrows indicate the changes of state to the present. Also indicated is the Pacific equilibrium longitude at 162.4°E. The dotted curve is the drift trajectory resulting from the last peroxide maneuver of 29 October 1965.

The trajectory is shown to terminate as of 7 December 1967, the date of the last orbital input as of this writing. At that time, the drift rate had reversed and Syncom 3 was drifting west at 0.003°/day; its position was 159.8°E longitude. Figure 3 represents approximately 1.5 years of using gas to control the satellite position near the stationary longitude. The changes of state appear erratic due to the inadequate knowledge and unpredictability of events during this period. Assuming that the consistency exhibited by the last three maneuvers with System 1 may be extrapolated into the future, the velocity corrections can be performed repeatedly with predictability. The drift trajectories would then appear as repeating soft limit cycles which are symmetrical with

TABLE 6. RESULTS OF GAS MANEUVERS

Maneuver Date	System	System Pressure, psia	Theory		Actual	
			I_{sp} , sec	\dot{m} , lb/sec	I_{sp} , sec	\dot{m} , lb/sec (average)
6/15/66	2	250 - 211*	62.4	0.074*	57.1*	0.0056*
8/24/66	2	211* - 179*	62.4	0.062*	57.1*	0.0044*
4/18/67	1	152 - 140	62.4	0.047	58.9	0.0027
5/17/67	1	140 - 121.5	62.4	0.042	56.3	0.0030
6/2/67	1	121.5 - 98.5	62.4	0.035	56.2	0.0029

*Based on I_{sp} derived from averaging actual specific impulses from System 1 maneuvers.

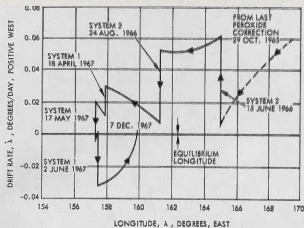


Figure 3. Syncom 3 Drift Trajectories

respect to the longitudinal axis. The longitudinal width of the limit cycle and its relative location to the equilibrium longitude determines the magnitude of the velocity corrections. The observed high resolution, i.e., 0.005 fps per pulse, could permit a narrow limit cycle band if it were required (e.g., by fixed ground antennas with narrow antenna beams). However, it is of primary importance for Syncom 3 to situate the limit cycle close to the equilibrium longitude where the acceleration due to triaxiality is small, thereby increasing the time a given control availability can keep the satellite visible between Hawaii and the Far East. The limiting factor in choosing this location is the uncertainty in the acceleration; i.e., although the

applied velocity increment is accurate, the error in the drift trajectory due to this uncertainty could cause overshoot of the equilibrium longitude.

Assume the limit cycles are centered at 160.4°E longitude, or 2°W of the Pacific equilibrium longitude. This is a conservative choice for the probable uncertainties in the drift acceleration. For a limit cycle 1 degree wide, a control capability of approximately 0.37 fps/yr is required; the latter is based on the drift acceleration presented in an earlier section of this paper. For the 3.7 fps combined control capability available in both Syncom 3 control systems, this limit cycle can be maintained for 10 years. In light of the problems which appeared during the past 1.5 years of stationkeeping with gas, it is not likely that this full capability can be so utilized. The opposite extreme is loss of all control so that no more maneuvers can be performed. The satellite will then continue to drift westward until it is beyond Hawaii's visibility; this will occur in late January or early February 1969. It is difficult at this time to predict where the Pacific orbital life of Syncom 3 lies between these extremes although the pessimistic result appears more probable.

References

1. R. E. Balsam and B. M. Anzel, "Determination of the Pacific Equilibrium Point for a Stationary Orbit," Journal of Spacecraft and Rockets, October 1967.
2. D. D. Williams, "Dynamic Analysis and Design of the Synchronous Communications Satellite," Hughes Aircraft Company, TM649, May 1960.