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THE SYNCOM III LAUNCH

by Forest H. Wainscott

Goddard Space Flight Center
Greenbelt, Md.

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ABSTRACT

The Syncom III spacecraft was launched from Cape Kennedy, Florida on 19 August 1964 with the three stage thrust-augmented Delta vehicle configuration using the ABL X-258 solid propellant motor as the third stage. Through appropriate adjustment of the Delta powered flight, the transfer orbit, and the apogee motor boost direction, a synchronous orbit with a final inclination near zero degrees was achieved. Subsequent maneuvering with the satellite's on-board hydrogen peroxide jet control system reduced the orbital eccentricity to zero and located the spacecraft over the International Date Line.

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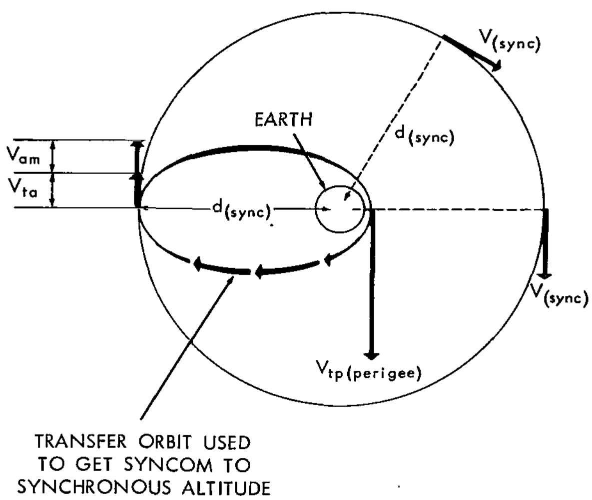
INTRODUCTION

Syncom II was launched successfully on July 26, 1963 and a few days later was maneuvered to its designated station at longitude 55°W. From that vantage point it provided 24-hour-a-day communications for most of the western world. While its placement on station represented a first and was an achievement that won wide acclaim, it was a relatively simple exercise compared to the effort required, about a year later, to place Syncom III, its nearly identical twin, in the desired orbit. Many restraints had conspired to give Syncom II a highly inclined orbit, which deprived it of a true stationary character and caused it to move in a figure eight pattern, symmetrical about the equator when viewed from the earth. Chief among these was the limited capability of the booster rocket. For the Syncom III launch, this restraint was removed by the addition of solid thrust-augmentation rockets on the booster and a larger third-stage rocket motor. The thrust-augmented Delta rocket has the boost capacity to permit changes in the orbit plane at crucial points during the launch and transfer orbit sequence; thus the launch-orbit plane may be brought into coincidence with the earth's equatorial plane while the satellite is boosted to synchronous orbit altitude and velocity.

LAUNCH SEQUENCE FOR A SYNCHRONOUS ORBIT

The Syncom satellites are placed in their final orbit by the use of an intermediate elliptical *transfer orbit* over which the spacecraft travels to an apogee distance equal to the radius of the desired synchronous orbit. The booster rocket vehicle has three stages, and a fourth stage—the apogee motor—is an integral part of the spacecraft. The first two stages boost both the satellite and the final two stages into an initial orbit called a *parking orbit*. At the apogee of the parking orbit the third stage is fired, boosting the satellite and last stage into the *transfer orbit*. Finally, the last stage is fired at the apogee of the transfer orbit, which is at synchronous orbit altitude. This may be done at the first apogee or delayed until the second or third apogee while orientation maneuvers are performed.



V_{am} = APOGEE MOTOR VELOCITY INCREMENT

V_{ta} = VELOCITY AT TRANSFER ORBIT APOGEE

V_{tp} = VELOCITY AT TRANSFER ORBIT PERIGEE

$V_{(sync)} = V_{am} + V_{ta}$ = SYNCHRONOUS VELOCITY

$d_{(sync)}$ = SYNCHRONOUS ORBIT RADIUS

Figure 1—Method of putting Syncom into a synchronous orbit.

During the launch the satellite is oriented so that at the transfer orbit apogee the apogee motor thrust will produce a total velocity vector tangent to the path of the desired circular orbit. The velocity increment so obtained is just that required to produce a circular synchronous orbit when added to the apogee velocity vector of the transfer orbit (Figure 1).

The powered trajectory of the three stage launch vehicle results in a transfer orbit whose apogee is 22,752 nautical miles from the earth's center; this is the altitude at which a circular orbit is synchronous, i.e., has a period of 24 hours. Various factors at Cape Kennedy constrained the initial orientation and launch direction of the booster vehicle: For example, the latitude of the launch site resulted in an inclination of 28.7 degrees for the parking orbit; but maneuvering of the Delta vehicle during powered flight reduced this inclination and brought the vehicle to the proper flight azimuth. In general, when synchronous, equatorial orbits must be achieved from launch sites off the equator, orbit plane changes are made at the perigee of the transfer orbit and/or at the apogee motor ignition point. The Syncom spacecraft was maneuvered in orientation to permit adjustment of the direction of the apogee motor thrust vector.

Syncoms I and II were placed in inclined orbits by using only the first half of the transfer orbit (apogee motor ignition at first apogee). To place Syncom III in an equatorial synchronous orbit, two orbital plane changes were required. The first of these was made at the perigee of the parking orbit: The second stage, during the coasting period after its burnout, was yawed 38 degrees left. This maneuver reduced the equatorial inclination of the transfer orbit after third stage burn by 12.2 degrees, to 16.5 degrees. Since a truly equatorial orbit plane was desired for Syncom III, another maneuver was needed to reduce the inclination to nearly zero. The change was again achieved by an appropriate addition of velocity vectors during apogee motor burn: An orientation maneuver at second apogee of the transfer orbit pointed the apogee motor in the proper direction, and its ignition at third apogee resulted in a velocity vector in the earth's equatorial plane at synchronous velocity. These plane changes are shown in Figure 2.

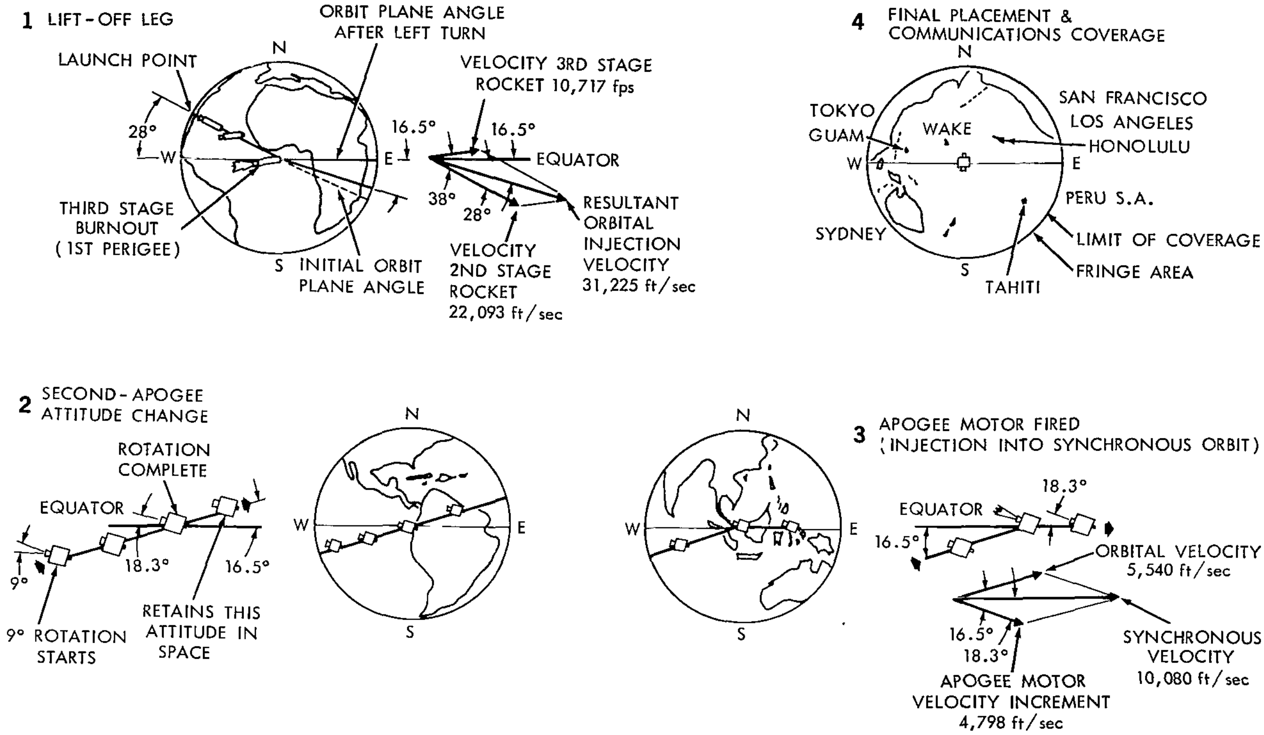


Figure 2—Syncom III orbital plane maneuvers.

SYNCOM III CONTROL SYSTEM

The Syncom III spacecraft control system consists of the components necessary to control the velocity and attitude of the spacecraft within the system limits. Control of the orbital velocity permits control of the orbit period and hence the position in longitude, in addition to permitting control of the orbital eccentricity and inclination. Attitude control is utilized in adjusting the orbital inclination and aligning the spacecraft spin axis. The control system incorporates two hydrogen peroxide jet systems and utilizes sun sensors for spin rate and attitude determination.

Each hydrogen peroxide jet system (Figure 3) includes two tanks, two solenoids, and two thrust chambers. One thrust chamber (axial jet) of each system is mounted parallel to and approximately 14 inches from the spacecraft spin-axis (at the apogee motor end) and produces a thrust parallel to the spin-axis. The second thrust chamber (radial jet), mounted at the circumference of the spacecraft and perpendicular to the spin axis, produces a thrust normal to the spin axis through the spacecraft center of gravity. The 4.9 pound hydrogen peroxide supply in each system is initially pressurized with nitrogen gas to 200 psia.

Operation of an axial jet in a continuous mode creates a thrust along the spin axis of the spacecraft. If the spin axis is in or near the orbital plane this operation will alter the orbital velocity by an amount depending on the duration of the thrust and the orientation of the spin axis. For a given period of operation the maximum orbital velocity change is obtained when the spacecraft spin axis is tangential to the orbit plane. With the spacecraft spinning, attitude changes are accomplished by pulsing an axial jet in synchronism with a particular portion of the spin cycle. The jets operate more efficiently in the continuous mode than in the pulsed mode because of the geometry and because of the specific impulse, which is approximately 157 sec in the continuous mode and 110 sec in the pulsed mode. The total spacecraft velocity capability of the jet control system is approximately 575 feet per second.

After the spacecraft is oriented to its final orbit position (spin axis normal to the orbit plane) the axial jets are used for minor attitude corrections and the radial jets for any necessary corrections to the orbital velocity. In either case the systems are operated in a pulsed rather than a continuous mode, and the pulses are synchronized with a particular portion of the spin cycle to produce the desired torque or thrust. Use of either the axial or radial jets in the pulsed mode operates the jets over 60 degrees of the spin cycle, giving a pulse duration of about 60 milliseconds for a spin rate of 160 rpm.

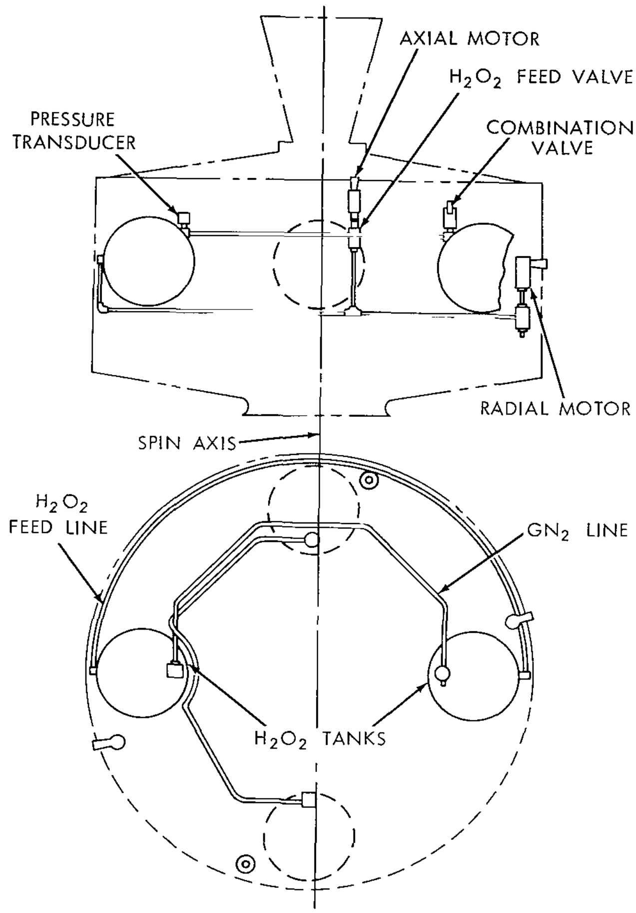


Figure 3—Syncom H_2O_2 control system.

DESCRIPTION OF THE BOOST TRAJECTORY

During the first stage portion of the flight the launch vehicle was rolled to a flight azimuth of 95 degrees from the true north; a four-step autopilot pitch program was initiated 4 seconds after lift-off and terminated 126 seconds later. Because there was insufficient time to roll the vehicle to the proper flight azimuth before initiation of the pitch program, a combined pitch, yaw, and roll maneuver was performed between 4 and 9.67 seconds after lift-off. The thrust-augmentation solid motors on the first stage had a burning time of approximately 27 seconds followed by a 13-second tailoff period; their empty casings were jettisoned at lift-off plus 70 seconds. The first-stage main engine continued to provide thrust for a total of 148.7 seconds, utilizing 99.6 percent of the propellant available for impulse. The vehicle conditions after the first stage burnout were the following:

Altitude:	60.4 n. mi.
Inclination:	28.6°
Eccentricity:	.628
Period:	44.4 minutes

The second stage ignition signal was given during the first-stage vernier engine operation 4 seconds after main engine cutoff (MECO). First-second stage separation occurred 4.3 seconds after

MECO, and the second stage attained 90 percent chamber pressure 0.1 second later. A pitch program was initiated at MECO plus 6 seconds and terminated 16 seconds before second-stage engine cutoff (SECO). The nominal second-stage burning time of 161.5 seconds corresponds to consumption of 96 percent of the propellants available for impulse. The spacecraft fairing was jettisoned during second stage powered flight, 14 seconds after MECO. After second-stage burnout the vehicle conditions were the following:

Altitude:	195.6 n. mi.
Inclination:	28.7°
Eccentricity:	.147
Period:	87.8 minutes

After nominal SECO, the second stage and the Syncom III payload coasted for 1255.2 seconds to second-stage apogee nearly over the equator. During this time the Delta second stage was yawed 38° left to align the thrust axis of the third stage. The firing of the third stage in the new direction reduced the inclination of the orbit from 28.7 degrees to 16.5 degrees. Just prior to the second-stage apogee, the spin rockets which spin up the third stage and payload were fired and the third-stage pyrotechnic time delay was initiated. Two seconds later, the second-stage gas retro system was activated and the second and third stages were separated. The third stage ignited 4 seconds after stage separation and burned for a nominal duration of 22.6 seconds. The vehicle conditions prior to and following third stage burning were the following:

	Pre-Fire	Post-Fire
Altitude	608.0 n. mi.	608.4 n. mi.
Inclination	28.7°	16.5°
Eccentricity	.146	.705
Period	87.8 minutes	674.9 minutes

The Syncom III spacecraft was separated from the third stage 47.4 seconds after third stage burnout and was allowed to drift through 2.5 transfer orbits.

The period of the transfer orbit was 11.25 hours. The point of injection into the transfer orbit is by definition, the perigee point; thus, the time to first apogee of the transfer orbit was approximately six hours. At that time, the spacecraft's orbit and attitude had to be determined so that the spacecraft could be re-oriented prior to the apogee motor firing. Syncom I and II experience had shown that 4 to 5 hours are required to determine the orbit accurately and about two hours to determine the spacecraft's orientation. In addition, a few hours were needed to calculate the spacecraft parameters for the re-orientation maneuver. Thus, there was not time to re-orient the satellite prior to the first apogee of the transfer orbit. Although sufficient time *was* available to re-orient the satellite and fire the apogee motor at *second* apogee, this was not desirable because the satellite would be located over South America: whereas the desired final position was over the International Date Line. At third apogee, however, the satellite would be located over Sumatra. On this basis it was decided to re-orient the satellite at second apogee of the transfer orbit and to fire the apogee motor at third apogee. This procedure allowed time to determine both the orbit and orientation of the spacecraft prior to the re-orientation at second apogee, and also to evaluate the resultant orientation and orbit after the maneuver. Sufficient time would also be available for a second maneuver prior to firing the apogee motor if that were necessary. Time would also be available to determine the precise firing time for the apogee motor.

The attitude of the spacecraft spin axis is defined by its right ascension (SARA) and declination (SADEC). The positive spin axis of the spacecraft is directed from the transponder antenna toward the apogee motor nozzle. After separation of the spacecraft from the third stage rocket, the most likely attitude of the spin axis corresponds to the direction of the third stage boost increment. In the case of Syncom III this attitude was: SARA 241.5°; SADEC 8.7°. However, the angle telemetered from the sun sensor by the TM 1 telemetry channel and polarization measurements from the spacecraft communications antenna failed to yield a suitable solution to the spacecraft attitude. The sun sensor measurement was 100.2 degrees. After several possible explanations had been considered, the most probable one was tried: the sign of the telemetered sun sensor angle from TM 1 was reversed. Satisfactory convergence of a solution for the spacecraft attitude was then achieved between the polarization data and the sun sensor data. Also, the telemetry was switched to TM 2 and the sign of the datum was opposite to that obtained from TM 1, verifying that the sun sensor angle was 79.8 degrees rather than 100.2 degrees.

The attitude of the spin axis determined from the corrected telemetry data was: SARA 229.3°; SADEC 3.5°. The angle between this direction and the direction of third stage boost was 13.1°. A later examination of the telemetry data showed that the third stage-spacecraft combination had been coning excessively following third stage boost, and that the spacecraft separation had occurred at 11.0 degrees from the nominal attitude. The difference between the two results is within the accuracy of the measurement. Since re-orientation of the spin axis during the transfer orbit was already planned as a part of the launch sequence, no serious problems resulted from the "tip-off" experienced. The spacecraft was simply precessed 21.6° rather than the previously planned 9° to correct for the "tip-off". The parameters of the first orientation maneuver on August 20, 1964 at 05^h 30^m 00^s Z are given in Table 1. Data from a ground calibration prior to launch resulted in essentially perfect maneuvering of the spin axis. Therefore, there was no need to maneuver the axis again prior to apogee firing.

Table 1

Parameters of Syncom III First Orientation Maneuver, 05^h 30^m 00^s Z. August 20, 1964. and Effect on the Orbit.

Parameter	Predicted Value	Actual Value
Pulsing time (sec)	31.0	31.0
No. of pulses .	86	83
Precession angle (deg.)	21.6	21.0
Propellant used (lb)	0.154	0.155
Velocity (ft/sec)	4.35	7.79
Spin axis (deg) right ascension	244.9	244.2
Spin axis declination (deg.)	18.9	18.7
Effect of Orientation Maneuver on the Orbit		
Semi-major axis (n. mi.)	13984.0	13983.5
Inclination (°)	16.71	16.70
Eccentricity	0.710	0.710
Longitude of Ascending Node (°)	330.5°	330.6°

APOGEE MOTOR FIRING AND FINAL MANEUVERS

Since the transfer orbit had slightly more energy than had been predicted prior to flight, an eastward drift rate after apogee motor firing could not be realized while making a near-optimum transfer to the near-synchronous orbit. Therefore, with the derived spin axis direction, it was expected that the impulse from the apogee motor would place Syncom III in an orbit which would be above synchronous energy (i.e., with a westward drift sense). The spin axis direction was selected to accommodate this situation, however. With the derived direction, the impulse from the apogee motor would over-correct the inclination (i.e., change the ascending node by about 180°), and produce an orbit with nearly zero inclination, with an eastward drift-rate. The apogee motor was fired at $17^h\ 17^m\ 56.25^s$ on 20 August. The parameters for the apogee motor firing are given in Table 2. The impulse from the apogee motor produced an orbit very close to that which was predicted, proving conclusively that proper orientation of the spacecraft had been selected at the time of the maneuver at second transfer orbit apogee. The various spacecraft maneuvers required after apogee motor firing to place the spacecraft in a zero inclination, zero eccentricity orbit at 180 degrees longitude are presented in order of occurrence in Table 3, along with the associated parameters. A description of each of these maneuvers will be found in Appendix A.

Table 2

Parameters of Syncom III Apogee Motor Firing.

Parameter	Predicted Value	Actual Value
ΔV (ft/sec)	4808.9	4822.5
Burn time (sec)	19.7	20.75
Resulting drift (°/day)	2.99W	3.28W
Eccentricity	.0448	.0438
Inclination (°)	.111	.208
Longitude of ascending node (°)	153.8°	140.6°
Spin axis right ascension (°)	244.2°	245.1°
Spin axis declination (°)	18.7	18.85

Table 3

Syncom III Orbital Maneuvers.*

Maneuver	Velocity (ft/sec)	Weight of Propellant Used (lbs)	No. of Pulses	Continuous Mode Jet-on Time (sec)	Orbit Eccentricity	Orbit Inclination (deg.)	Resulting Drift (deg/day)	Spin Axis Right Ascension (deg.)	Spin Axis Declination (deg.)	Precession Angle (deg.)	Time of Correction
1st Velocity Corr.	102.8	1.69	-	102.3	.0253	.307	7.12E	245.1	18.85	-	$04^h\ 55^m$ Z 8/22/64
2nd Reorientation	6.8	.18	142	-	-	-	-	243.1	-11.4	31.0°	$14^h\ 00^m$ Z 8/28/64
2nd Velocity Corr.	25.2	.47	-	32.6	.0175	.312	3.30E	243.1	-11.4	-	$14^h\ 02^m$ Z 8/28/64
3rd Reorientation	23.4	.37	233	-	.0157	.128	-	25†	-86.6	81.4	$18^h\ 00^m$ Z 9/3/64
3rd Velocity Corr.	46.3	1.10	758	-	.0065	.125	2.06W	5.4†	-85.1	-	$10^h\ 30^m$ Z 9/10/64
4th Velocity Corr.	9.7	.26	182	-	.0046	.096	1.01W	3.5†	-84.9	-	$22^h\ 45^m$ Z 9/10/64
5th Velocity Corr.	9.1	.26	185	-	.0028	.095	.01W	-14.6†	-84.0	-	$22^h\ 40^m$ Z 9/11/64
4th Reorientation	1.8	.05	23	-	-	-	-	-	-90.0	8.6	$22^h\ 50^m$ Z 9/25/64
Inclination Corr.	21.0	.34	-	22.5	.0028	.066	-	-	-90.0	-	$22^h\ 51^m$ Z 9/25/64
6th Velocity Corr.	6.3	.19	127	-	-	-	-	-	-	-	$08^h\ 51^m$ Z 10/1/64
7th Velocity Corr.	6.7	.20	138	-	-	-	-	-	-	-	$20^h\ 50^m$ Z 10/1/64
8th Velocity Corr.	1.2	.05	29	-	.0001	.058	.00	-	-90.0	-	$08^h\ 48^m$ Z 10/2/64

*Additional small maneuvers of a "station keeping" type have been made since this report was prepared.
†This angle is not well defined for a spin axis declination near ±90°.

CONCLUSION

While its predecessor Syncom II demonstrated the world's first synchronous orbit, it remained for Syncom III to demonstrate the first truly "stationary" orbit. All objectives of the Syncom III mission were met. Every system on board the spacecraft is presently operating as designed. The orbital elements for Syncom III issued on October 3, 1964 by Goddard Space Flight Center were:

Epoch	2 October 1964, 1035.00 hours U.T.
Semi-major Axis	42167.60 km
Orbital Eccentricity	0.00020
Inclination	000.059 deg
Mean Anomaly	070.144 deg
Argument of Perigee	346.553 deg
Motion Plus	000.0268 deg/day
R. A. of Ascending Node	293.168 deg
Motion Minus	000.0134 deg/day
Anomalistic Period	1436.20066 min.
Motion Plus	0.00000 min/day
Height* of Perigee	35780.94 km
Height* of Apogee	35797.67 km
Velocity at Perigee	11071 km/hr
Velocity at Apogee	11066 km/hr
Geocentric Latitude of Perigee	-00.014 deg

The location of the satellite is at 179.93° West longitude. The orbital elements differ only slightly from those of a perfect synchronous, non-inclined, non-eccentric orbit, and the limitation preventing a perfect orbit is the theory used for orbit computation. The spacecraft control system can provide velocity increments of 0.05 ft/sec and can control the orbit several orders of magnitude better than the orbit can be measured.

Following placement of Syncom III on station, approximately 175 ft/sec of control system capability now remains. This velocity increment is sufficient for many years of satellite station keeping (correcting for perturbations by the sun, the moon, the earth's triaxiality, etc.).

(Manuscript received July 30, 1965)

*Above mean sea level.

Appendix A

Description of Syncom III Orbital Maneuvers*

1st Velocity Correction

Syncom III remained in the orbit resulting from the apogee motor boost for 1-1/2 revolutions, at which time axial jet No. 2, operating in the continuous mode, was used to reverse the direction of drift. The objective was to change the drift from 3°/day westward to 7°/day eastward (to cause the satellite to approach the desired 180° longitude rapidly) and to reduce the eccentricity of the orbit.

Combined 2nd Re-orientation and 2nd Velocity Correction

The objectives of this maneuver were (1) to position the spin axis so that subsequent maneuvers would produce a zero inclination orbit, and (2) to reduce the rapid eastward drift rate to allow more time to determine the plane of the orbit. The maneuver was accomplished using axial jet no. 2, first in the pulsed mode to effect the re-orientation and then in the continuous mode to effect a change in orbital velocity.

3rd Re-orientation

The objective of this maneuver was to orient the spin axis normal to the equatorial plane so that the spacecraft communications antenna pattern would cover the earth 24 hours per day. The maneuver was accomplished with axial jet no. 2 in the pulsed mode.

3rd Velocity Correction

By the time this maneuver was made, Syncom III had drifted east to 180° longitude and was at 178° west. This was planned as a feature of the maneuver sequence, since the first part of the maneuver was designed to raise the perigee of the orbit to the synchronous radius, and a westward drift rate would unavoidably result. The maneuver was accomplished with lateral jet no. 1 in the pulsed mode.

*Additional small maneuvers of a "station keeping" type have been made since this report was prepared.

4th Velocity Correction

To achieve a stationary orbit at 180° longitude from this point in the maneuver sequence, three more velocity corrections would have been required at about 12 hour intervals. This approach was deemed unreasonable at the time from the standpoint of available manpower; therefore, a compromise in the position was made and only two more maneuvers were planned. The first one, or the fourth velocity correction, was accomplished 12 hours later using radial jet no. 1 in the pulsed mode. This maneuver was designed to produce a westward drift rate such that one orbital period subsequent to the maneuver time, the satellite would be in a position to be synchronized at a mean longitude of 180 degrees.

5th Velocity Correction

This maneuver was designed to synchronize the orbit of Syncom III at a mean longitude of 180 degrees, was performed with lateral jet no. 1 in the pulsed mode and established the initial synchronous orbit on September 11, 1964. The orbital eccentricity was .0028, and the daily excursion in longitude due to this eccentricity was from 179.68° W to 179.68°E with a mean of 180.00°. The excursion in latitude was ±.095 degrees due to the inclination of 0.095 degrees.

Combined 4th Re-orientation and Inclination Correction

The objectives of this combined maneuver were (1) to finely position the spin axis normal to the equatorial plane, and (2) to adjust the orbital inclination so that one week subsequently (allowing for perturbations due to the sun and the moon) the orbit could be made stationary by using the lateral jets. The maneuver was performed with axial jet no. 1, first in the pulsed mode to effect the re-orientation and then, in the continuous mode to effect the inclination correction.

6th, 7th and 8th Velocity Corrections

The purpose of this series of three maneuvers was to establish a circular orbit at 179.97 degrees West longitude with an initial drift rate of .011 degrees per orbit West. Such an orbit would cause Syncom III to remain within 0.03 degree of the desired longitude of 180 degrees for the maximum period of time, 22.2 days, without additional corrections. All three maneuvers were accomplished within 24 hours by using the lateral jets, without intermediate orbit determination.

NASA-Langley, 1966

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