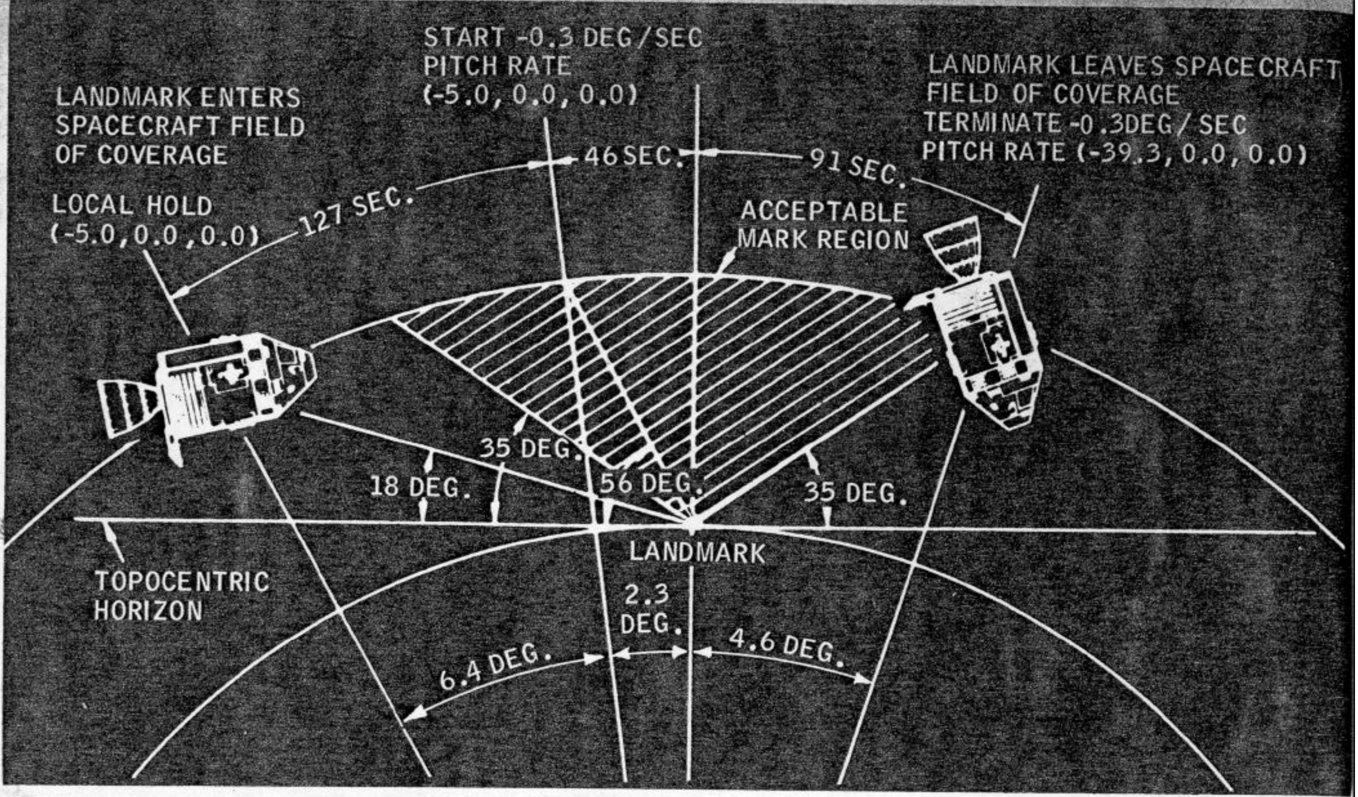


Landmark tracking attitude sequence used in lunar orbit required pitching at —0.3 deg./sec. rate to maintain landmark within optical subsystem's field of view. Pitch rate began 46 sec. before passing closest point to landmark and 91 sec. afterward.

Space Technology

Apollo 8 Proves Value of Onboard Control

Precision of guidance, navigation demonstrates feasibility of moon flight without need to rely on ground-based aids

By B. K. Thomas, Jr.

Houston–Accuracy of the guidance and navigation control system onboard the Apollo 8 during its lunar-orbit mission last month demonstrated that astronauts can return safely from the moon without the aid of earth-based tracking aids.

The system also provided lunar landmark tracking data which will play a major role in developing the mission profile for landing men on the moon.

The spacecraft control system demonstrated accuracies which permitted the Apollo 8 astronauts to delete four of the seven midcourse corrections anticipated during the six-day flight.

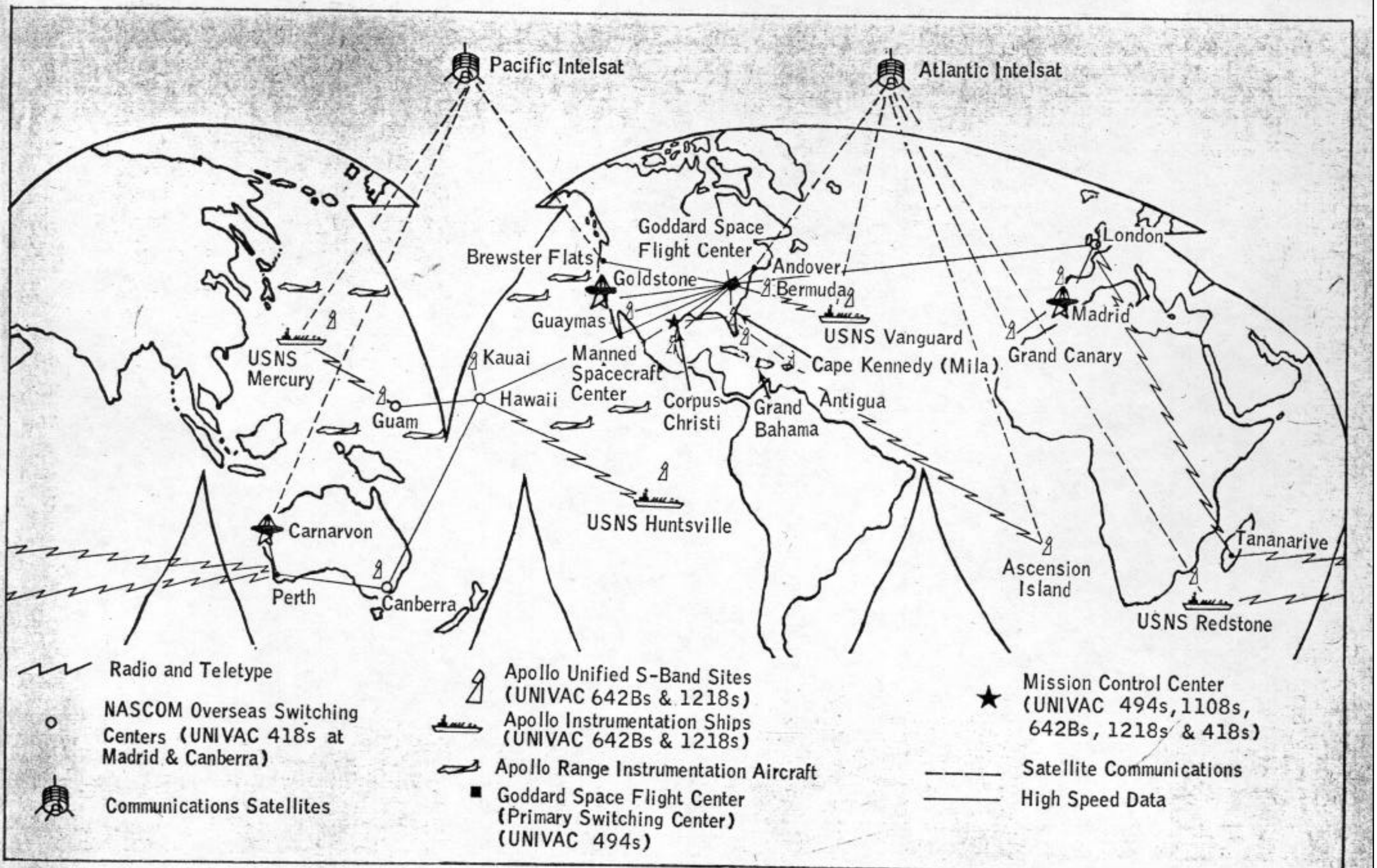
Vehicle state vector, which defines the spacecraft's estimated position and velocity along the trajectory at any time during the mission, showed a close correlation on board with the state vector data generated by the National Aeronautics and Space Administration's manned space flight network. The network (see chart) is the primary means of controlling Apollo spacecraft.

Either system can provide position and velocity for the spacecraft, Christopher C. Kraft, Jr., NASA's director of flight operations, said at the conclusion of the flight. "In almost every comparison we made, there was just a high degree of accuracy, which is not to be expected the first time you use complicated systems like that."

The onboard Apollo control system was designed by the instrumentation laboratory of the Massachusetts Institute of Technology. AC Electronics Div. of General Motors produced, integrated and tested it. The unit has three major subsystems:

- **Inertial guidance subsystem,** composed of an inertial measurement unit and associated equipment. This subsystem, produced by AC Electronics, performs three major functions: (1) it measures changes in spacecraft attitude, (2) measures spacecraft velocity due to thrust and (3) assists in generating steering signals.
- **Optical navigation subsystem,** produced by Kollsman Instrument Co., includes a space sextant and a scanning telescope. The sextant is a 28-power optical instrument with a 2-deg. field of view. The one-power telescope has a 60-deg. field of view. Sightings on celestial bodies and landmarks on the moon and on the earth are used by the computer subsystem to determine the spacecraft's position and velocity and to align the inertial reference within the inertial measurement unit.
- **Command module computer,** produced by Raytheon Co., provides five major functions: (1) it calculates steering signals to keep the spacecraft on the required trajectory, (2) positions the stable member in the inertial measurement unit to a coordinate system defined by precise optical measurements, (3) positions the optical unit to celestial objects, (4) conducts limited malfunction isolation of the guidance and control system by monitoring the level and rate of system signals and (5) supplies pertinent spacecraft condition information to the vehicle's display and control panel. Included as part of the computer subsystem is the onboard guidance and navigation display and keyboard through which the crew can insert data and commands into the computer.

Onboard navigation procedures em-



Apollo communications network includes aircraft, ground stations, ships and use of Intelsat satellites over Atlantic and Pacific.

ploying the optical subsystem to align the inertial measurement unit required the crew to obtain sightings on three reference stars each time alignment of the unit was checked.

Through commands to the onboard computer, generated by the crew with the computer's display keyboard, the optical subsystem was directed at one of a series of reference stars whose coordinates were stored in the fixed memory of the computer.

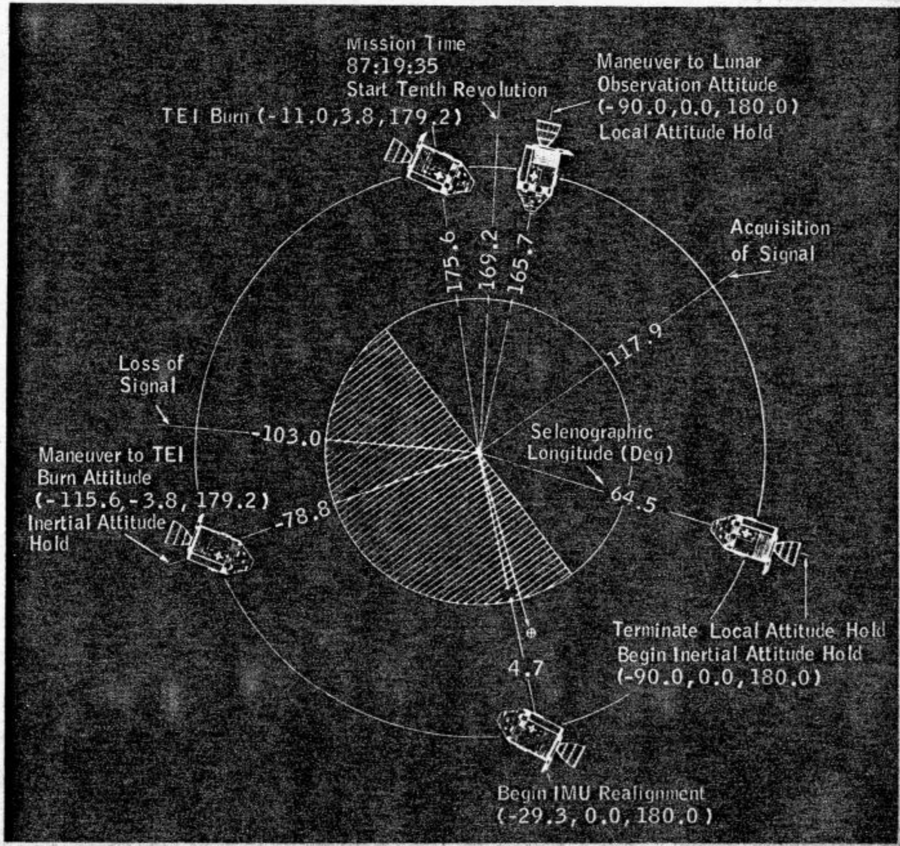
When the star was accurately located in the sextant of the optical subsystem and the operator depressed the mark button on the optics control panel, the measurement of the angle between the line-of-sight to the star and the base line of the optical subsystem was inserted into the computer. The procedure was repeated using each of the other two reference stars.

Alignment of the inertial measurement unit was then calculated and performed automatically by the computer using the data from the sightings.

A similar procedure was employed using the optical subsystem—while sighting on a reference star and the horizon of the earth or moon—in determining the need for midcourse correction maneuvers during translunar and transearth coast phases of the mission.

Guidance and navigation subsystem is used in conjunction with the stabilization and control, service propulsion, reaction control, electrical power, environmental control and telecommunications subsystems on the spacecraft.

After the spacecraft was inserted on a translunar trajectory at 2 hr. 50 min. 30 sec. ground elapsed time, modifica-



Spacecraft orientation for service propulsion system posigrade burn at end of 10th revolution placed crew heads down for visual reference with lunar surface. Relative to local horizontal orientation, attitude included pitch angle of —11.0 deg., yaw angle of —3.8 deg. and roll angle of 179.2 deg. Burn put Apollo 8 into transearth trajectory.

tion to the flight plan was made to include a midcourse correction at 11 hr. A 2.4-sec. burn of the spacecraft's service propulsion system at that time, while the Apollo 8 was 52,770 naut. mi. above the earth, provided a 24-fps. velocity change.

The magnitude of this correction enabled the prescribed trajectory to be regained following an earlier trajectory change, which provided additional separation between the spacecraft and the spent S-4B third stage of the booster.

Calculation of the vehicle state vector by ground controllers, using data derived by the spaceflight network, and the crew, with its control system, disclosed that the next two midcourse corrections were not required. They were tentatively planned to have occurred at 27 hr. 30 min. ground elapsed time and at 47 hr. 11 min., with a 1.1-fps. velocity correction for the former and a 3.3-fps. velocity correction for the latter.

Vector Updates

These state vector updates were "almost small enough to be at the level that you are not sure whether that's the midcourse or the uncertainty [at the specified times] of the orbit definition," said Glenn Lunney, Apollo 8 flight director.

Based upon the capabilities of the ground control network, the threshold of uncertainty for conducting midcourse corrections was 1 fps., according to Lunney.

Next midcourse correction occurred at 61 hr. This correction, a retrograde thrusting maneuver performed with the service module's reaction control system, supplying a 400-lb. thrust for 12 sec., provided a 2.2-fps. decrease in the velocity of the spacecraft. The vehicle weight at the time of the correction was estimated to be 62,888 lb.

Midcourse Correction

Immediately following the midcourse correction, the Apollo 8 was traveling 4,107 fps. at a distance of 28,676 naut. mi. from the moon. Comparison between the ground controllers and the flight crew showed close agreement in predicting the pericynthion of the spacecraft. Ground controllers predicted it to be 61.5 naut. mi. and computations by the crew determined it to be 63.0 naut. mi.

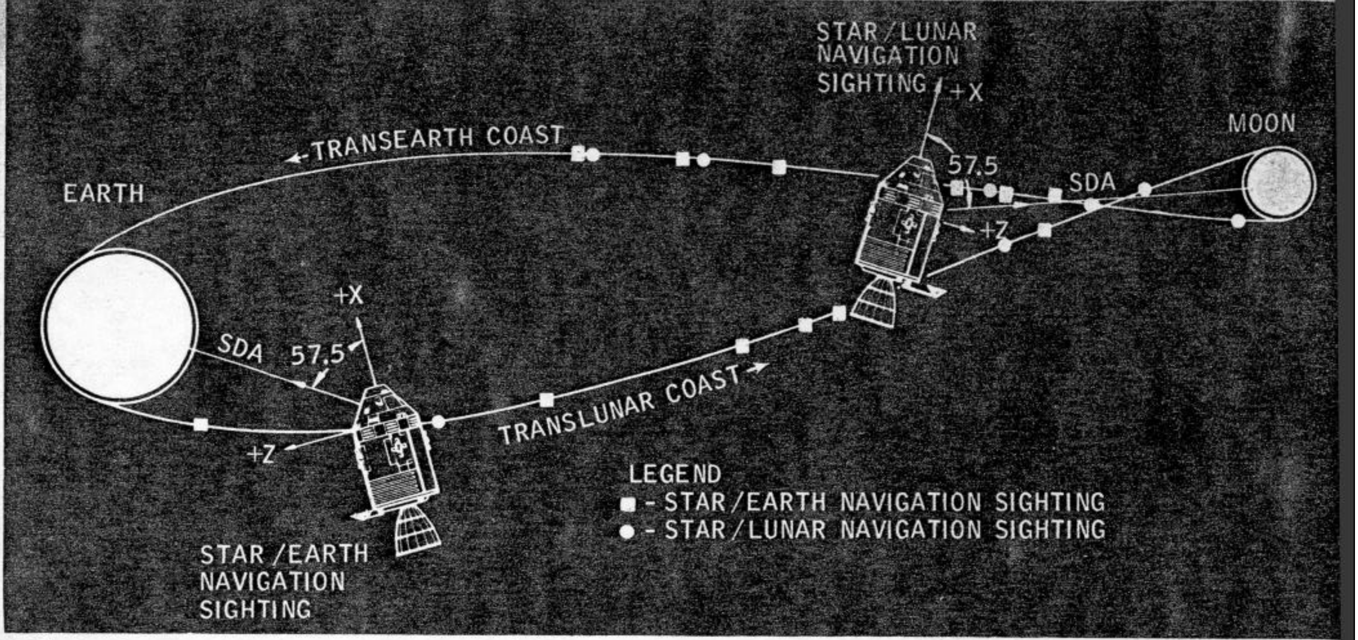
Further midcourse corrections to the spacecraft's trajectory were unnecessary before the Apollo 8 crew commanded firing of the service propulsion system to reduce the velocity and place the spacecraft into lunar orbit.

Loss of the signal with the spacecraft, as it swung behind the moon prior to lunar orbit insertion, occurred at 68 hr. 58 min. 45 sec. Under command of the computer of the onboard guidance and navigation system, retrograde thrusting of the service propulsion system engine occurred on time at 69 hr. 08 min. 52 sec. to place the Apollo 8 into lunar orbit. Thrusting for 4 min. 6.5 sec., the service propulsion system reduced the spacecraft velocity by 2,990 fps. from more than 7,777 fps., enabling the Apollo 8 to enter lunar orbit.

At this point, determination of the spacecraft's pericynthion and apocynthion by the crew compared closely with that of the ground control network. Onboard readings showed a pericynthion of 60.5 naut. mi. and an apocynthion of 169.1 naut. mi., against 60.4 and 168 naut. mi., respectively, on the ground.

Circularization of the spacecraft's orbit about the moon, occurring at the start of the third orbit, showed further close agreement between flight and ground computations following the burn. The burn was performed while the spacecraft was in a retrograde attitude, with the crew heads down to provide visual reference with the lunar surface. Retrograde thrusting of the spacecraft's reaction control system for 11 sec. occurred at 73 hr. 35 min. 05 sec., reducing velocity by 135 fps. and providing a near-circular orbit.

Onboard determination of the space-



Apollo 8 orientation for cislunar navigation operations during translunar and transearth coast phases had to meet requirements for communications and avoidance of gimbal lock in onboard guidance and navigation system, as well as for optical pointing requirements. Pre-mission planning determined that maintaining local horizontal attitude with shaft drive axis of optical subsystem aligned at 57.5 deg. to center of reference body would provide favorable attitude to meet requirements.

craft's pericynthion and apocynthion following the burn were 60.8 naut. mi. and 62 naut. mi., respectively; ground network computed values were 60.5 and 60.9 naut. mi.

Prime test objective of the Apollo 8 mission was to gain data from landmark tracking exercises in lunar orbit for a manned landing on the moon. The main objectives were:

- Establish error uncertainties in lunar landing site locations using onboard data from sighting on lunar landmarks.
- Obtain data to calibrate the manned space flight network at lunar distance.
- Determine the sun angle at which lunar landmarks can be identified with the clarity required for tracking.
- Determine whether lunar landmark tracking can be accomplished on the portion of the lunar surface illuminated by the earth.
- Evaluate the adequacy of the guidance and optical subsystems of the spacecraft's onboard guidance and navigation control system for obtaining landmark sightings.
- Verify the ability of Apollo crews in lunar orbit to coordinate sightings and vehicle maneuvers as required for landmark tracking.
- Determine reaction control system propellant requirements and the times needed to accomplish landmark sighting exercises.

Apollo 8 crewmen obtained a mass of data to determine in the weeks ahead how well they achieved their objective. According to their remarks while conducting the tracking exercises, they left little doubt they were successful.

"I used the auto optics for control points 1 and 2 on the back side and they worked beautifully," Capt. James A. Lovell, Jr., said while describing some of the landmark tracking exercises he performed behind the moon while using the optical subsystem.

"Frank [spacecraft commander Col. Frank Borman] pulled the target for me and I went to the control point 3 as designated in our orbital control book, just using the latitude and longitude given to me, and used auto optics to track that coordinate system, but it was very close to the actual tracking spot," Lovell said.

The data obtained during the landmark tracking exercises may provide information to the variation in the spacecraft's pericynthion and apocynthion due to mass concentrations in the lunar surface.

Information obtained from the Lunar Orbiter mission has determined variations in the orbit of those spacecraft circling the moon which are believed to vary the altitude of the orbit. Data from the Apollo 8 flight confirmed the existence of these perturbations. Further analysis is necessary to ascertain whether it is of enough magnitude to adversely affect the control of orbiting Apollo spacecraft by the earth-based manned space flight network.

Because the primary mode of spacecraft navigation while in lunar orbit is performed by the network, definitive information is required on orbital variations so that the network data, providing vehicle state vector update, is accurate.

During the tracking exercises, data from the ground network compared well with the guidance and navigation computer on the spacecraft, mission controllers reported. At times variation in velocity readouts between the two was as little as 1 fps. However, additional analysis, to be performed with the data obtained from the Apollo 8 flight, is expected to resolve more adequately the effects, if any, that mass concentrations may have on data the network supplies the spacecraft.

To help resolve this ambiguity, one method to be employed in postflight analysis will be to compute the position updates of the lunar landmarks and compare the positions derived from Lunar Orbiter data. Postflight analysis also will include comparing landmarks in photographs which were taken from the Apollo 8 spacecraft against known lunar features and navigational sighting data.

Postflight analysis will seek to determine instrument accuracy of landmark sightings utilizing the scanning telescope of the optical subsystem on board the spacecraft and the acceptability of the optics image from the spacecraft of lunar landmarks at orbital altitudes.

Analysis of the Apollo 8 crew ability to observe details of the lunar surface in earthshine and the ability to track over the lunar surface will utilize ground network data defining the orbit and comparing it with the positions established from the Lunar Orbiter flights.

Ability of the crew while in lunar orbit to perform consistently accurate landmark tracking and orbital navigation will be based on their comments, spacecraft maneuvering rates and sighting accuracy and repeatability of data for a particular landmark.

Landmark tracking, commencing in the fifth orbit, began with the spacecraft stabilized in the initial landmark

Ghetto Business Faces Marketing Problem

Boston—EG&G Roxbury is undergoing a reorganization that reflects what is likely to be a central problem of emerging black community business—the marketing confrontation.

Although EG&G has a contract from General Electric's Aircraft Engine Group at Lynn, Mass., for metal stampings, some other expected business did not materialize last year. This was true in particular for a small business set-aside contract that could have run over a year's time.

As many subcontractors have learned, small business set-asides may be more a political promise than production. EG&G Roxbury found that a competitor in this case was bidding a total price of less than the cost of material alone to EG&G.

Other proffers of business from companies did not develop, but EG&G Roxbury believes the offers were sincere. It is retaining its basic community-operated and ownership concept, but to meet the problem, it is cutting back on overhead. Production employes charged to direct labor are being retained, and none of the trainees has been dropped.

EG&G Roxbury will report to the parent company, EG&G Inc., through E. Van Noorden Co., which EG&G acquired last year (AW&ST June 10, 1968, p. 44). EG&G Roxbury is occupying facilities that had been used by Van Noorden, a metal fabricator in the commercial field which was sought by EG&G, Inc., as a product line source for the Roxbury operation.

Richard W. Richardson, who joined EG&G Roxbury after having been production manager for metal working at Digital Equipment Corp., Maynard, Mass., has been named operations manager, succeeding Bertram M. Lee, who had been general manager.

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tracking altitude, which was a pitch of −5.0 deg. with respect to the local horizontal. This attitude was maintained locally fixed until the spacecraft was about 46 sec. from the closest point of approach to the landmark.

The spacecraft was then given a −0.3 deg./sec. pitch rate to keep the landmark in the optics field of coverage throughout the tracking period. Approximately 91 sec. after the spacecraft passed the closest point of approach to the landmark, the pitch rate was terminated.

Sighting Sequence

Following tracking of the landmark, the spacecraft was returned to the initial landmark tracking attitude for a repeat of the landmark sighting sequence on a pseudo landing site landmark. After completion of the sighting sequence on the pseudo landing site landmark, the spacecraft was rolled 180 deg. to gain S-band high-gain communications, and the resulting attitude was held inertially fixed. This attitude satisfied the requirements for the inertial measurement unit realignment, which occurred approximately 10 min. later, after the spacecraft entered darkness.

Realignment of the inertial measurement unit was performed on each lunar orbit during periods of darkness.

Landmark tracking maneuvers performed on succeeding orbits began from the initial landmark tracking attitude and utilized the sighting sequence of maintaining a constant −0.3 deg./sec. pitch rate, commencing about 46 sec. prior to the landmark and continuing through approximately 91 sec. past the landmark. This kept the landmark in the optics field of coverage.

During the ninth revolution, the spacecraft was placed into a lunar observation orientation, which included a pitch of −90 deg., with respect to the local horizontal, and a roll of 180 deg., following loss of the network line of sight.

The lunar observation orientation was held locally fixed until about 10 min. after the spacecraft entered sunlight, when it was maneuvered to the attitude planned during the transearth insertion burn. While in this attitude, a star check with the sextant of the optical subsystem of the onboard guidance and navigation was performed.

At the beginning of the 10th revolution, the spacecraft was returned to the locally fixed lunar observation attitude. Approximately 20 min. before the spacecraft entered darkness, the local attitude hold was terminated and the existing attitude was held inertially fixed. This attitude satisfied the requirements for the inertial measurement unit realignment, which began as the spacecraft entered darkness.

About 7 min. before loss of the spaceflight network line of sight, the inertial hold attitude was terminated and the vehicle was maneuvered to the transearth insertion burn attitude. Measured from the local horizontal, this attitude included a pitch angle of −11.0 deg., yaw angle of −3.8 deg. and roll of 179.2 deg.

Transearth insertion burn occurred at a ground elapsed time of 89 hr. 19 min. 16 sec. Duration of the thrustin by the service propulsion system wa 3 min. 23 sec., providing a velocity increase of 3,522 fps. The boost in velocity increased the spacecraft's speed from 5,331 fps. to 8,853 fps. to inser it into the planned transearth trajectory

After completion of the service propulsion system thrusting to send the spacecraft back toward earth, the weigh of the Apollo 8 command and service module had dropped to 31,739 lb.

Correction Maneuver

Next midcourse correction maneuver controlled by the onboard guidance computer occurred on time at 104 hr. elapsed time, while the spacecraft was 167,548 naut. mi. from the earth. Thrusting was performed with the reaction control system for a burning time of 14 sec.

Spacecraft attitude during the burn required orienting the spacecraft 90 deg. away from a radius vector extending from the center of the earth. The purpose of maintaining this attitude during the burn was to modify the trajectory so that the spacecraft would pass more nearly through the center of the entry corridor into the earth's atmosphere more than 42 hr. later.

Velocity change in the desired direction was 5 fps.

Following this midcourse correction, periodic update of the spacecraft's state vector by the ground controllers and the Apollo 8 crew determined that a midcourse correction, planned for 122 hr. elapsed time, was unnecessary. Further update of the state vector at 140 hr. into the mission disclosed that a final midcourse correction, planned to occur 2 hr. prior to entry into the earth's atmosphere, also was unnecessary.

"You'll be within 0.06 deg. of your entry angle target line," ground controllers told the Apollo 8 crew while canceling the final midcourse correction.

Precise Trajectory

During the remainder of the flight, the onboard guidance and control system steered the Apollo 8 spacecraft along a precise trajectory from the point where the midcourse correction occurred at 104 hr. elapsed time through entry corridor, commencing at 400,000 ft. altitude.

For proper entry, the spacecraft had to be guided so that it entered the atmosphere at a −6.5 deg. angle, measured from the local horizontal, within ±1 deg. at a velocity of 36,220 fps. During the entry phase of the mission, the onboard guidance and navigation control system was in full control of the spacecraft, monitoring bank angles to ensure that the flight path did not exceed the desired limits (AW&ST Jan. 6, p. 28).