MARINER MARS 1969 NAVIGATION, GUIDANCE, AND CONTROL*

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ABSTRACT

Design, mechanization, and flight test results of the Mariner Mars 1969 navigation, guidance, and control systems are summarized. A trajectory design section describes near-earth launch trajectory, planetary targeting, and constraints, as well as the tradeoffs made on the trajectory selection. Among the factors considered are reliability, direct ascent vs parking orbit, and higher spacecraft weight vs extended launch window. Guidance and orbit determination factors are discussed, including earth-based radio and spacecraft optical navigation and the accuracy of orbit determination and maneuver execution.

The control systems section identifies differences in the attitude control, midcourse maneuver, and science instrument scan pointing systems from those used in previous Mariner spacecraft. A description is given of the new Central Computer and Sequencer (CC&S) system, used for the first time on this mission, which allows extremely flexible spacecraft operation using in-flight reprogramming of the computer memory by radio command. Finally, reliability summaries and performance evaluations permit conclusions as to the effectiveness of the Mariner Mars 1969 navigation, guidance, and control systems to conduct near-term and more advanced planetary missions.

INTRODUCTION

The Mariner Mars 1969 Project was authorized in December 1965 by the National Aeronautics and Space Administration to conduct two flyby missions to Mars during a launch period beginning February 24, 1969. The Atlas-Centaur, used earlier for the Surveyor unmanned lunar landing program, was selected as the launch vehicle. The 1969 Mars flyby is a follow-on to the 1964 Mariner and provides a foundation for the 1971 and 1973 Mars missions.

Primary mission objectives are study of the atmosphere and surface of Mars as a basis for future experiments to determine existence of extraterrestrial life.[1] A secondary objective is to develop technology for succeeding Mars missions. The 1969 Mars mission will be unable to detect life on Mars, but it will help to establish suitability of the Martian environment for life.

TRAJECTORY CHARACTERISTICS

Use of the Atlas-Centaur for Mariner 1969 offers a unique advantage over previous Mariner missions. The Mariner Mars 1969 spacecraft is the first in the Mariner series to have a greater weight capability from the launch vehicle than that required. This excess payload capacity was used to add spacecraft redundancy, to reduce the flight time and communication distances, to allow for a longer launch period, and to use a more reliable direct-ascent trajectory.

The two spacecraft of the Mariner Mars 1969 Project have trajectory designs to allow them to pass by the planet within 5 days of each other, although they are launched more than 1 month apart. An undesirable characteristic of these higher speed trajectories is that the velocity of the spacecraft relative to the planet is increased by about 50%. This is compensated for by a more flexible scientific instrument pointing system on the spacecraft, which allows multiple scans of the desired features, thus increasing the amount of observation time at encounter from the 20 min of Mariner IV to 24 min of Mariner Mars 1969.

Selection of the aiming zones for the two spacecraft is shown in Fig. 1. Both spacecraft are designed to obtain the maximum possible scientific data about Mars, although either flight alone would provide valuable data if the other were not totally successful. The two aiming zones chosen were a near-equatorial area and a point that would allow a view of the south polar cap. Both trajectories pass within approximately 3500 km of the surface on a path that permits earth occultation but not occultation of the sun or the guide star Canopus. Initial aiming points selected for the launch vehicle trajectory were sufficiently above the planet to assure planetary quarantine and the final aiming zones are reached by midcourse correction after separation from the launch vehicle.

GUIDANCE AND ORBIT DETERMINATION

Guidance of the Mariner Mars 1969 uses ground-based radio orbit determination. Communication with the spacecraft is accomplished by the Deep Space Network (DSN), consisting of nine permanent space communications stations located on four continents. Except for the Mars 210-ft-diameter antenna at Goldstone and the monitoring station at Cape Kennedy, all sites have 85-ft-diameter tracking antennas. Each tracking station is equipped with multiple receivers and is able to send radio commands to the spacecraft.

Radio data consist of one-way or precision two-way tracking which yields information on two angles, radial velocity, range, and telemetry. The Mars 210-ft-dish provides a 9-dB increase in performance over the standard 85-ft stations and is used for critical operations. The trajectory is designed so that the closest approach to Mars will occur while in view of the 210-ft-diameter antenna.

Accuracy requirements for orbit determination are increased over previous missions. The size of the aiming zone for Mariner Mars 1969 is compared with those of previous missions on Fig. 2. The 3σ dispersion of the trajectory at Mars after one midcourse correction is decreased from the 10, 000 km of Mariner 1964 to 1, 000 km in Mariner 1969. This is the result of increased accuracy of both ground and spacecraft guidance systems, including use of ranging data and a double-precision orbit determination program. The ephemerides and constants of the solar system are improved over those used in 1964.

After injection, the trajectory of the spacecraft is determined and data to carry out a mid-course maneuver are transmitted to the spacecraft. Each spacecraft is capable of making two midcourse corrections, at 5-15 days after launch, and if required, from 90-130 days after launch. The midcourse information transmitted consists of angles for pitch and roll turns, velocity increment, and time of initiation of the maneuver. The spacecraft is designed to carry out the maneuver automatically and return to its celestial references.

Approach Guidance, a new type of trajectory determination, will be attempted on an experimental basis during the Mariner Mars 1969 mission.(3) Optical measurements of the direction to Mars will use outputs of instruments carried on the spacecraft. Angular offsets will be telemetered from the sun sensors, Canopus tracker, and Far Encounter Planet Sensor (FEPS), along with television pictures of the planet. The data obtained will provide an independent trajectory determination whose errors are uncorrelated with those of the ground-based system. Potential accuracies of optical approach guidance orbit determination are shown in Fig. 3.

CONTROL SYSTEMS

The attitude control system is shown in Fig. 4. This system employs attitude references of three single-axis gyroscopes and/or sun and star sensors. The output of these references is processed by switching amplifiers to generate the necessary control signals for the output actuators. The actuators include 12 cold-gas jets for cruise attitude control and 4 jet vanes used for control during trajectory corrections.

Primary and secondary sun sensors provide a 4π steradian error signal that is used as the pitch and yaw attitude reference for acquisition and cruise modes of operations. These sensors are CdS photodetectors connected in pairs so that the output is proportional to the pitch or yaw sun displacement. When the spacecraft is within approximately 4.5 deg of the sun, the secondary (or acquisition) sun sensors are switched out.

Angular reference for the roll axis is provided by the Canopus star tracker.[4] Collecting optics focus the star image on the face of an image dissector tube which generates a roll error signal and a light intensity signal. The roll error signal provides cruise attitude reference, and the intensity signal is used in logic circuitry to discriminate the star Canopus from other celestial objects.

The Canopus tracker incorporates high- and low-gate intensity detection circuits that reject a celestial object if it is too bright or too dim. These gates may be set by internal logic or adjusted by ground command. The Canopus sensor design prevents loss of control caused by bright particles passing through its field of view. The field of view of the Canopus tracker must also be adjusted in the direction perpendicular to the roll axis to accommodate the apparent variation in the Canopus direction as the spacecraft travels around the sun. At approximately 4-week intervals, this field of view is changed by the CC&S or radio command system. All angular error detection and field of view adjustment is accomplished electronically using no moving parts.

Three single-degree-of-freedom floated gyros provide either rate signals or position plus rate to the pitch, yaw, and roll attitude control systems. Gyros are operated in a torque rebalance mode and the type of output error signal desired may be selected by the choice of networks used in the feedback loop. Gyros used in a rate mode provide damping signals and rate stabilization during initial separation and acquisition phases. Gyros in a position plus rate mode provide references for controlled turns and for the midcourse maneuver autopilot. During the normal cruise mode of flight, gyros are switched off and damping signals are provided by derived rate networks. The roll gyro may also be used for inertial control of the spacecraft, if the Canopus sensor fails.

Nonlinear electronics process the error signals to control the output actuators, by using switching amplifiers that provide a deadband of ±4.0 mrad in the pitch and yaw axes and ±4.3 mrad about the roll axis. The amplifiers have an additional nonlinearity of a 20 ms minimum on-time to provide the equivalent of hysteresis in the limit cycle.

The midcourse maneuver autopilot uses a different set of electronics from the attitude control system. The autopilot system controls attitude during engine firing by using gyros to sense attitude and rate errors about the spacecraft's three axes and positions the jet vanes. Each jet vane has its own separate servoamplifier and, since the midcourse motor is not oriented along any principal axis of the spacecraft, each vane is controlled by a mixture of signals from each of the three gyros.

The gas system is divided into two sets of six jets, each complete with its own titanium pressure vessel, regulator, and lines; a failure of any valve to open or close will not jeopardize the mission. Each system contains 2 1/2 lb of dry nitrogen gas pressurized to 2500 psi. Both sets operate simultaneously during a normal mission; however, either system can support the entire flight in the event of failure of the other.

The scan control system provides angular control of a 2-degree-of-freedom gimballed platform on which the science instruments are mounted. It is positioned by command signals from the CC&S or in a closed-loop tracking mode. The position sensor used for closed-loop tracking is the FEPS, which tracks the center of brightness of the planet.

During the far encounter sequence, the platform is oriented to a fixed reference direction by CC&S command, and then the FEPS orients the scientific instruments toward the planet for a series of television pictures. In the near encounter sequence, control is returned to the CC&S, which positions the platform through a series of pointing directions. Directions may be updated in flight by radio commands.

CENTRAL COMPUTER AND SEQUENCER

The CC&S for Mariner Mars 1969, shown in Fig. 5, is a completely new subsystem.(5) Previous Mariners employed a simple fixed-sequence device with a series of events preprogrammed and hard-wired prior to launch.(2) The only events that could be changed after launch were turn durations, midcourse velocity increment, and time of midcourse. The Mariner Mars 1969 CC&S consists of a midcourse maneuver sequencer, similar to those used on previous Mariners, plus a computer whose output controls the execution of various CC&S events. The computer portion of the CC&S is programmed with a set of data words and instructions that result in the desired sequence of events. Although this flight program is loaded into its 128-word memory prior to launch, the CC&S may be completely reprogrammed in flight by radio command. The contents of a single word or the entire memory may be interrogated during flight by use of the command and telemetry systems. Midcourse maneuver events are generated in a tandem mode with both the fixed sequencer and the computer providing redundant outputs. Outputs of the two units are compared and, if a difference exists, the maneuver is aborted. An abort will reset the midcourse logic and initiate reacquisition of the celestial references. Cause of the failure can be determined by analysis of the telemetry, and a second attempt at the midcourse maneuver can be made using the correctly performing unit.

The major subsystems of the CC&S are the clock, the input decoder, the memory plane, a group of registers for temporary storage, a central processor, a group of output actuators, and the maneuver fixed sequencer. Sixteen instructions programmed into the computer control the flow of information to and from the computer memory and auxiliary data storage registers. Data used by these instructions are also stored in the memory. All information is stored in the form of 22-bit words. Coding in these words indicates the type of instruction, a memory address, an event time, and/or an event code used to select which output event will occur at the time corresponding to the time code. Events may be programmed to occur with a resolution of 1 h, 1 min, or 1 s.

FLIGHT RESULTS

Mariner VI was launched at 01:29 GMT, February 25, 1969, 15 min after the opening of the launch window on the first available day. Injection occurred at 01:41 GMT, and 1.5 min later the spacecraft separated from the launch vehicle. The sun was acquired at 01:58 GMT, less than 2 min after the spacecraft came out of the earth's shadow. A roll search was initiated at 05:25 GMT, and Canopus was acquired at 05:42.

The Mariner VI midcourse maneuver was initiated at 00:27 GMT, February 28, 1969. During motor burn duration of 5.35 s, the Canopus sensor was left on, although it was not in control of the spacecraft. The output of the tracker indicated that it observed bright particles during and after the period of combustion, due either to the rocket exhaust plume or dust particles shaken off the spacecraft similar to those seen by previous spacecraft.[2, 4, 6] After the maneuver, the spacecraft automatically reacquired the sun and Canopus. Since the spacecraft was displaced only 23.3 deg from the sun line during the pitch turn, it was able to remain on power from the solar panels throughout the maneuver.

Mariner VII was launched at 22:24 GMT, March 27, 1969. Separation occurred at 22:35 GMT; however, the spacecraft immediately entered the earth's shadow, and sun acquisition did not occur until 23:14 GMT, 2 min after it again saw the sun. Six min after roll search began, the Canopus tracker locked on the star Vega and it was left in that orientation until telemetry from launch and acquisition could be evaluated. A power transient occurred during separation from the launch vehicle, causing the CC&S memory to be interrogated by the telemetry system. It was determined that the spacecraft had suffered no damage and all systems were operating normally. On April 1, 1969, a roll override command caused the spacecraft to drop its lock on Vega and to acquire Canopus.

The Mariner VII midcourse maneuver was unique relative to any previous United States mission. Sirius, rather than Canopus, was the roll axis reference for the beginning of the commanded turns. The purpose was to avoid a pitch turn which could cause the Canopus tracker to look close enough to the sun to activate an automatic sun shutter. Accordingly, the spacecraft was rolled to acquire Sirius approximately 3 h prior to the beginning of the normal pitch and roll turns.

The Mariner VII spacecraft accomplished the rest of its midcourse maneuver normally on April 3, 1969, although bright particles during the motor burn were again observed.

Results of the two midcourse maneuvers are shown in Fig. 6. Trajectory determination as of June 3, 1969, indicates that the two trajectories will pass within 400 km (1σ) of the aiming points and well inside the aiming zones specified by the science investigators.

The Mariner VI and Mariner VII spacecraft pass Mars on July 31 and August 5, 1969, respectively, at about 1 min of the time planned prior to launch. The time of closest approach for Mariner VI is 05:19 GMT and that of Mariner VII is 05:01 GMT. These times of closest approach have been selected to allow the best coverage of the planet and to allow an overlap of the regions photographed.

A minor difficulty in the Mariner VI Canopus tracker was observed on April 20, 1969, when the cone angle position of the tracker should have been updated automatically by the CC&S. A celestial object near the south ecliptic pole, the larger Magellanic Cloud, was mapped by the Canopus tracker with the spacecraft under inertial control. The spacecraft was commanded to an orientation that would put the center of the Canopus tracker on the brightest spot of the cloud, and control was then turned over to it. Because of the diffuse nature of the cloud, the error signal from the Canopus tracker was not smooth and after a period of several hours, the spacecraft attitude reference slipped off the Magellanic Cloud and drifted to a nearby star. On the last day before Canopus disappeared from the edge of the field of view of the tracker, the spacecraft was directed back to Canopus and commands were again sent to change the cone angle position of the sensor. This time the effort was successful and the spacecraft was firmly locked on the desired star. The Mariner VI spacecraft had been under partial gyro control for a period of 261 h continuous running time during this sequence.

When the Mariner VI scan platform was unlatched by an explosive squib, bright particles again passed through the field of view of the Canopus tracker. Mariner VII was put under gyroscopic control when its scan platform was unlatched. Although bright particles were again seen, the spacecraft attitude was not disturbed. The encounter sequence near the planet was initially designed to operate under Canopus tracker control. After the occurrence of bright particles following each event in which spacecraft acceleration or shock impulse occurred, it was decided that several hours of the near planet encounter sequence should be under gyro control. The CC&S in both spacecraft were completely reprogrammed by ground command to modify the automatic sequence to warm up the gyros, disconnect the Canopus tracker, and initiate gyro control at the appropriate time. Thus, the spacecraft can carry out the entire planetary encounter sequence automatically in the event of failure of the command system.

During the flights of Mariners VI and VII, the CC&S has been reprogrammed many times by ground command. As of June 17, 1969, Mariner VI had received 575 radio commands and Mariner VII, 217. The number of commands sent to Mariner VI exceeds those which have been transmitted to all of the preceding Mariners combined. The flexibility allowed by the reprogrammable CC&S permitted the operations team to carry out many sequences not previously planned. It has also enabled alternative approaches to problems occurring in other spacecraft subsystems.

SUMMARY AND CONCLUSIONS

The navigation, guidance, and control systems of the Mariner Mars 1969 spacecraft successfully accomplished the mission requirements. Use of proven concepts demonstrated during previous Mariner flights has again shown the soundness of the Mariner design.

The new computer-organized CC&S permitted many operations not heretofore possible. Inflight accuracy achieved by both the launch vehicle guidance system and the spacecraft midcourse maneuver exceeded that obtained on any previous Mariner mission.

Flight performance of the guidance and control systems was as predicted prior to launch except for a problem of the Canopus cone angle update circuitry on Mariner VI. The improved Canopus tracker background rejection and acquisition logic enabled a more automatic Canopus acquisition. The bright dust particle problem observed on previous spacecraft was still present, although improvement in the Canopus tracker brightness logic prevented any serious consequences.

This was the first time that two planetary spacecraft have been successfully operated at the same time in the near vicinity of Mars. Operational problems caused by the simultaneous operations were eliminated by the enhanced capability of the Mariner 1969 navigation, guidance, and control systems, particularly of the CC&S, which enables events to be carried out automatically with few or no additional ground commands during critical periods.

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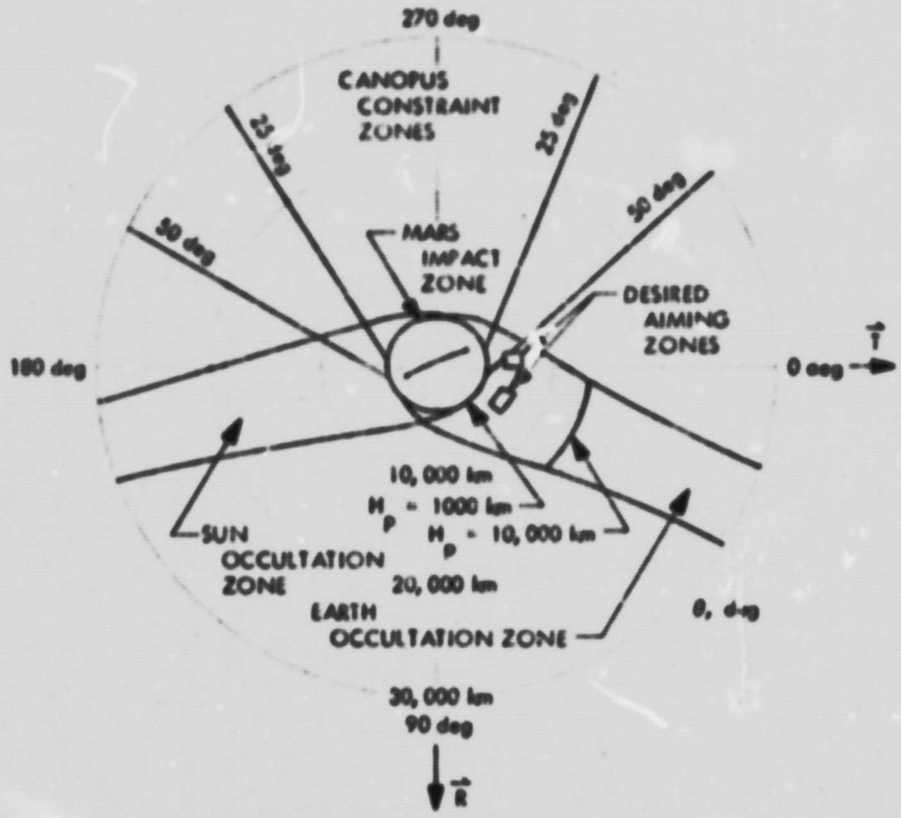

Fig. 1. Desired aiming zones at Mars

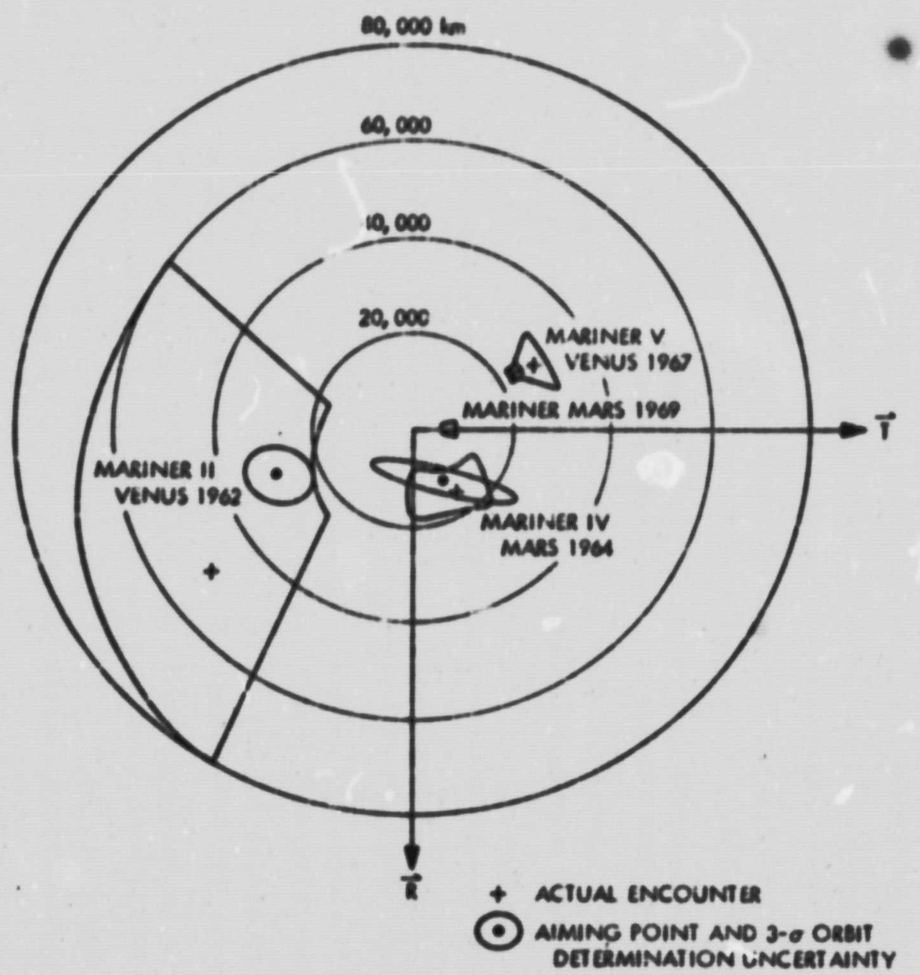

Fig. 2. Midcourse maneuver aiming zone anc. 3σ errors

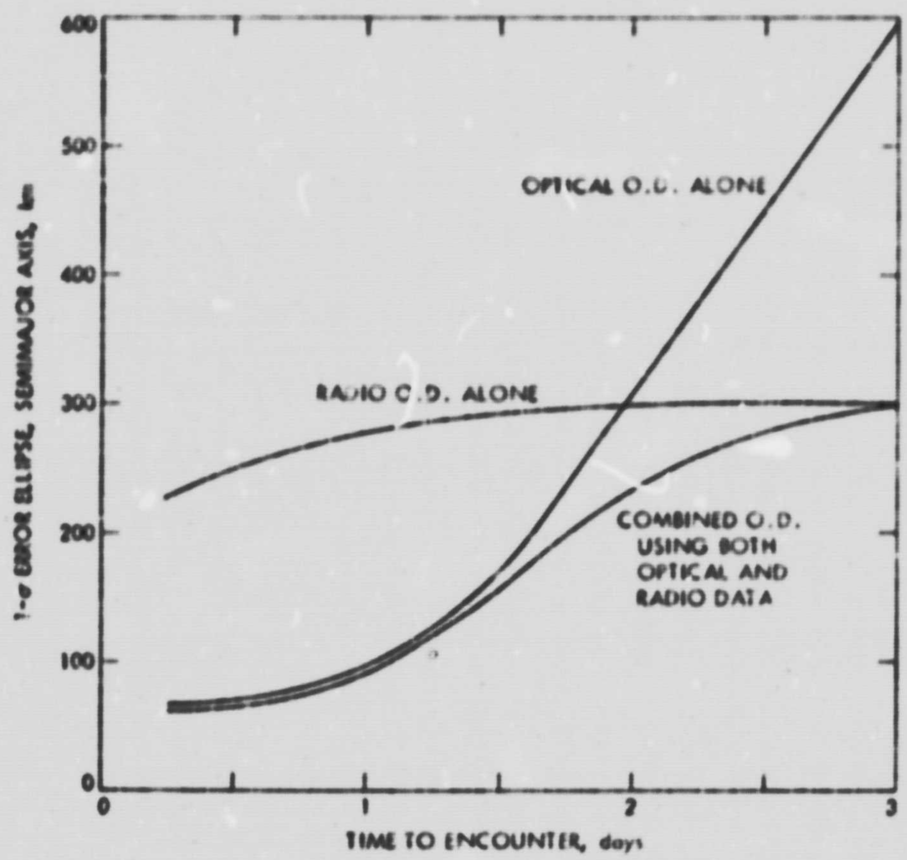

Fig. 3. Approach guidance orbit determination (O. D.) accuracy vs time

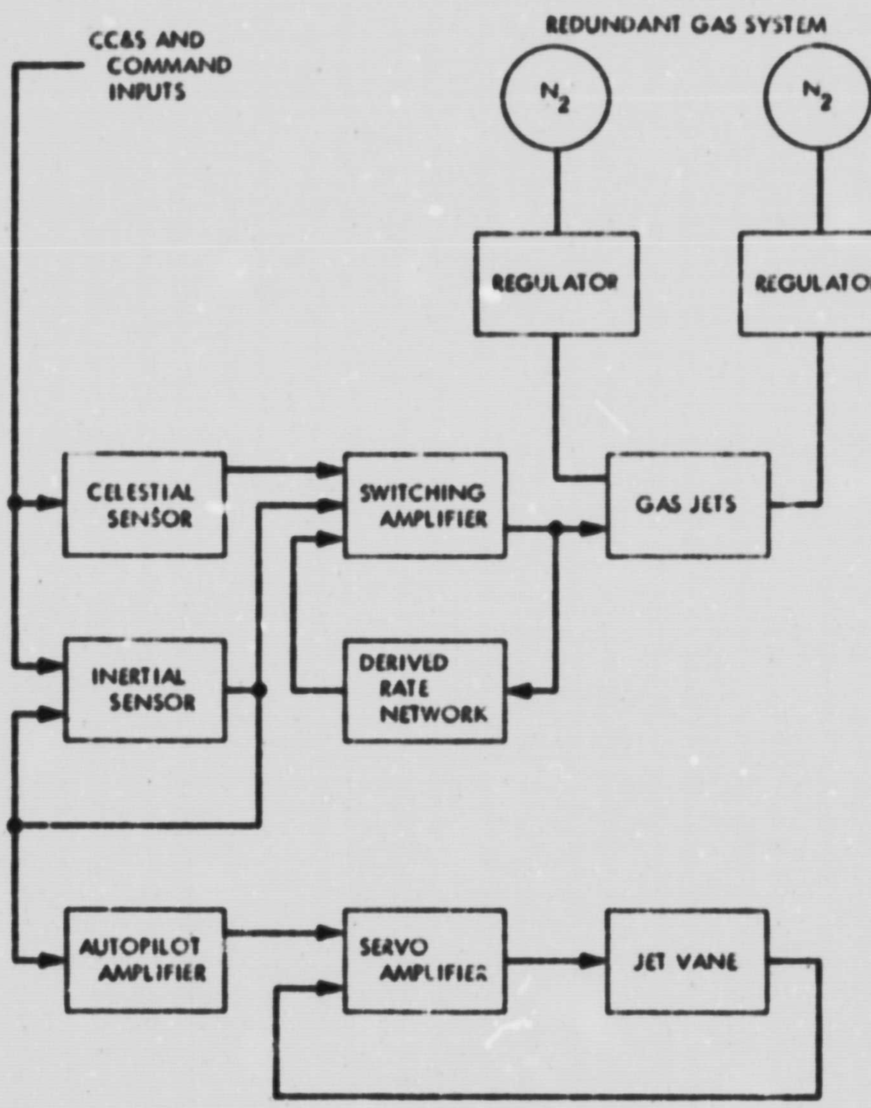

Fig. 4. Block diagram of attitude control system

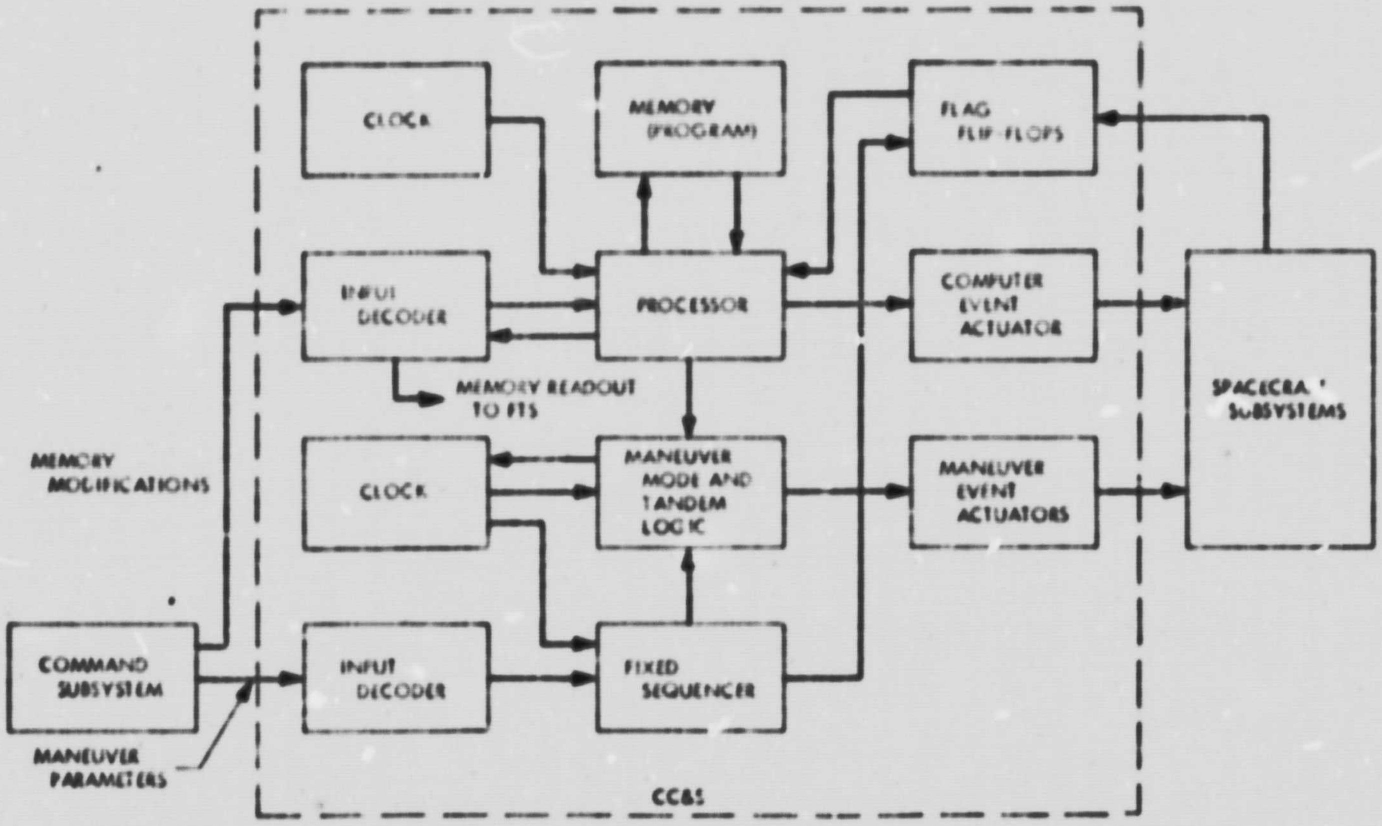

Fig. 5. Block diagram of Central Computer and Sequencer

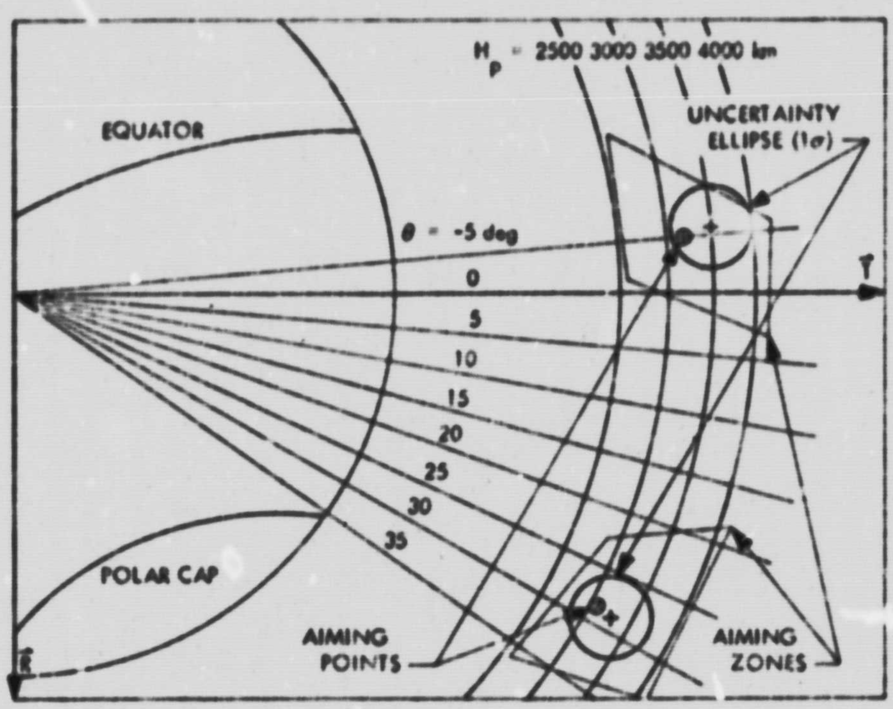

Fig. 6. Mariner VI and VII encounter geometry