Mariner Mission to Venus and Mercury in 1973

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The year 1973 presents an unusual opportunity to fly a single spacecraft to both Venus and Mercury. NASA plans to take advantage of this opportunity, and the Mariner Venus/Mercury 1973 (MVM '73) project has been established to carry it out. (Project management for MVM '73 was assigned to JPL in December 1969.) The two-planet mission has these objectives:

1. To conduct exploratory investigations of Venus and Mercury—measuring environmental, atmospheric, surface, and body characteristics. First priority is assigned to Mercury investigations.
2. Secondarily, to perform experiments in the interplanetary medium and to obtain experience with a dual-planet gravity-assist mission.

The MVM '73 project still being in its early stages, with many key aspects of the mission yet to be decided, this article necessarily treats the preliminary mission planning phase—background of the project, characteristics of the 1973 opportunity, and some possible mission options being considered.

Background: The opportunity to go to Mercury by Venus (swing-by) was first identified by Minovitch,[1] who showed the dual advantages of this mode: First, considerably lower launch energy than a direct mission to Mercury and, second, the bonus of close scientific investigation of Venus. Sturms surveyed the six Earth-Venus opportunities of this decade (1970, 1972, 1973, 1975, 1977, 1978) and found that only two—1970 and 1973—permitted flights on to Mercury with reasonable flyby altitudes at Venus and real advantage in lower launch energy.[2] Although the planetary configuration approximately repeats every eight years, the 1978 Venus opportunity does not constitute a Venus/Mercury opportunity. The high inclination, eccentricity, and mean motion of Mercury make a very accurate repeat of planetary positions necessary to obtain similar trajectory conditions.

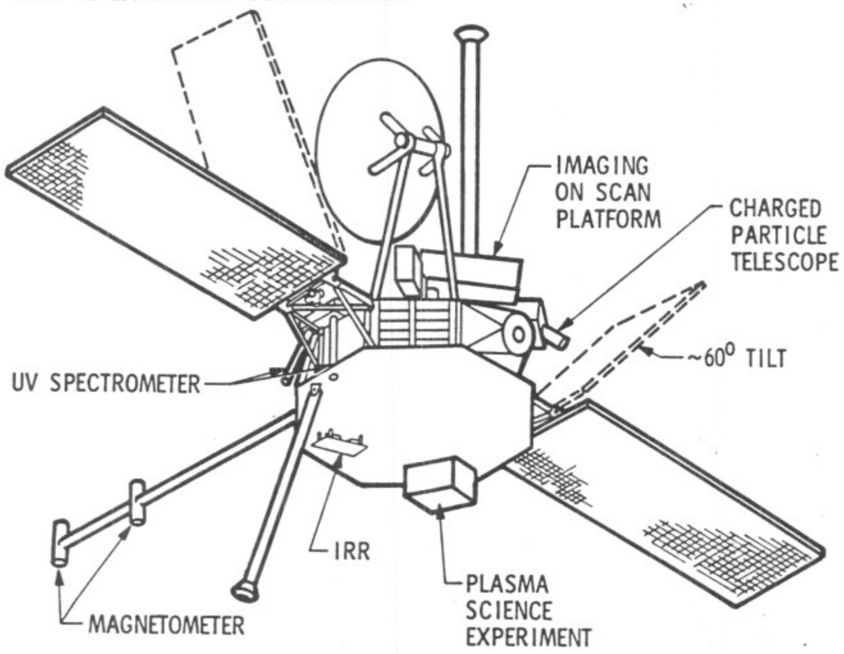
As the dual-planet mission was by-passed in 1970, the 1973 opportunity becomes the one time in the 1970s that an Atlas/Centaur can launch a Mariner-class spacecraft to Mercury passing by Venus at an altitude of 1000-6000 km. The 1973 conditions permit, moreover, a considerable range of arrival conditions at Mercury, and so considerable choice of scientific measurements.

Mission and spacecraft designs have been evolving since the first system-level study of a spacecraft to fly the 1973 mission was undertaken at JPL in late 1966.[3] Eckman gave a general discussion of the mission as of June 1969.[4] A JPL report describes the details of the design at that point.[5] This article depicts the project as we turn into the new year, and emphasizes trajectory characteristics.

Science Payload: A science payload for this mission was tentatively selected in July 1970. The table on page 55 lists experiments and principal investigators.

Many of the experiments resemble those flown on earlier Mar-

MVM '73 SPACECRAFT CONFIGURATION



iners. For instance, the television derives from the TV on the MM '71 orbiter, but the optics have been modified so that both cameras give high resolution. (See the August 1970 *A/A*, p. 64, for a complete discussion of MM '71.) The celestial-mechanics and radio-science experiments will be enhanced in this mission by the addition of an X-band spacecraft-to-Earth link coherent with the S-band signal. This will allow separation of charged-particle effects along the signal path. All experiments will benefit from a greatly increased data rate. For the first time it will be possible to send *full-resolution TV pictures in real time from Venus.*

Spacecraft: The MVM '73 spacecraft, shown on page 52, will look much like previous Mariners, its configuration based on the MM '69 and '71 hardware and technology. The "baseline" configuration of components is still flexible and changing, of course, and in final form may differ somewhat from the sketch shown.

The higher solar intensity encountered on this mission makes just two solar-cell panels adequate for power. The two fully celled panels ride outriggers to decouple them thermally from the spacecraft bus, and these members can be folded away from the Sun to limit the solar-cell temperature. Louvres on six of the bus' eight bays regulate its internal temperature. The propulsion subsystem occupies one of the remaining bays. A sunshade and thermal blankets shield the spacecraft bus and most of the instruments.

Two low-gain antennas mounted on opposite sides provide communications throughout the mission for all spacecraft attitudes. The high-gain directional antenna, a 48-in.-diam circular parabolic reflector on a 2-deg-of-freedom hinge, is mounted on the side of the bus. The TV-camera scan platform rides in the shade behind the central bus. An extendable boom to one side holds two magnetometers to isolate them from the spacecraft's magnetic field.

During cruise, the spacecraft axes are aligned relative to the Sun and the star Canopus through the use of celestial sensors. Gyros give an inertial reference for other necessary orientations, as in trajectory-correction maneuvers. An autopilot control subsystem stabilizes the spacecraft during burning of the trajectory-correction motor. This control system uses the gyros as the error sensors and jet-vane actuators to set the thrust vector.

A modified version of the MM '69 propulsion system—using anhydrous hydrazine and rated at 50-lb thrust in vacuum—generates impulse for trajectory corrections. Timed engine firings, controlled by a central computer and sequencer (CC&S), determine impulse magnitude. A blowdown propellant-feed system, with a multi-start capability, is being considered for the mission. Also, the motor needs a new bladder that will not cause excessive propellant decomposition under the higher heating rates near Mercury. An alternative configuration is being studied in which the motor axis is mounted parallel to the roll axis.

The CC&S, based on the MM '71 design, generates the timing and sequencing functions for the spacecraft subsystems throughout the flight. It is a stored-program special-purpose digital computer with a fixed sequencer for maneuver redundancy.

A new flight data subsystem (FDS) samples the science and the engineering measurements and does any necessary onboard processing before data transmission to Earth. This new subsystem permits the telemetering of more functions than before and at a higher rate. For the science instruments, the FDS provides the fine timing pulses to control such functions as multiplexer stepping and calibration. Multiple telemetry data streams range from 8⅓ bits/sec for engineering data during cruise to 117,600 bits/sec for real-time TV at Venus. An all-digital tape recorder, based on the MM '71 design but modified for record rates of 117,600 and 2450 bits/sec, stores data. This recorder will be used to record and play back 882 full-resolution pictures taken at Mercury. Some 2775 quarter-resolution pictures will also be transmitted in real time from Mercury. A half-disc mosaic composite of these pictures will be equivalent in resolution to the best Earth-based pictures of the Moon.

The telecommunications subsys-

This first U.S. spacecraft to Mercury will sweep by Venus – in the initial use of the gravity-assist technique expected to play a prominent role in outer-planet missions – pass close to the Sun's nearest neighbor, and, half a year later, owing to an unusual condition of celestial mechanics, possibly revisit it for further studies tem (117,600 bits/sec) will be a modification of the MM '71 unit, whose maximum data rate is 16,200 bits/sec. An X-band transmitter has been added to support the celestial-mechanics and radio-science experiments.

Characteristics of the 1973 Opportunity: The first detailed trajectory analysis for this mission was published by Sturms, who emphasized the flyby of Venus.[6] Since mission objectives now stress Mercury, it is appropriate to review this information in a form more suitable for Mercury mission design. The chart on page 56 shows contours of constant launch energy (C_3)—defined as twice the energy per unit mass of the spacecraft at Earth escape (in km^2/sec^2)—as related to the spacecraft weight that can be flown with the particular launch vehicle. For instance, an Atlas/Centaur can launch a spacecraft in the 900-lb class on a trajectory with $C_3 \leq 21$ km^2/sec^2. Hence, Atlas/Centaur can launch a spacecraft in this class on any trajectory with launch and arrival dates inside the $C_3 = 21$ km^2/sec^2 contour. Charts and diagrams on pages 56-57 include trajectories with launch energies up to 29 km^2/sec^2 to completely cover the 1973 opportunity.

Each pair of Earth-launch and Mercury-arrival dates defines a unique trajectory and completely specifies the flyby conditions at Venus; i.e., for a given trajectory there is no flexibility in the Venus encounter. A chart on page 57 shows one of the Venus flyby parameters — the altitude of closest approach (radius used, 6052 km). It presents, of course, a hard boundary to the available trajectories at zero altitude.

A set of diagrams on page 56 shows Mercury as it would appear from an approaching spacecraft—for six trajectories having a common launch date of October 24, 1973, and different arrival dates. Each picture shows the Earth and Sun occultation zones in the plane normal to the incoming asymptote (the aiming plane). The spacecraft can be targeted to any point in this plane; the selected aiming point will dictate the flyby geometry. If the aiming point falls within the occultation zones, the spacecraft will be hidden from the Sun and Earth as it passes by Mercury. Vectors *R* and *T* define an aiming-plane coordinate system, *T* being perpendicular to the incoming asymptote and parallel to the ecliptic, and *R* completing a right-handed set.

For progressively later arrivals, the Earth occultation zone moves from alignment with *T* to alignment with *R*, the planet as seen from the approach asymptote becomes more illuminated, and the prime meridian moves into the dark. On March 26, 1974, Mercury is at aphelion and the prime meridian lies on the terminator. (This occurs as a result of the prime meridian definition—passing through the subsolar point at the instant of perihelion passage on May 1, 1968, and the synchronism of Mercury rotational and orbital periods.[7])

For reasons discussed in the next section, a March 30, 1974 Mercury arrival (see page 57) has been selected.

Mercury Flyby: Selection of the arrival date and targeting at Mercury depends on the scientific requirements of the experiments flown. Although these requirements have not been fully developed, they can be generally placed into the following categories:

1. Imaging.
2. Nonimaging but planet-oriented (UV spectrometer and IR radiometer).
3. Fields and particles (plasma science, charged-particle telescope, and magnetometer).
4. Celestial mechanics and radio science.

Requirements for the different categories vary considerably. In general, the lowest and slowest possible trajectories prove most desirable for the experiments.

The imaging experiment will obtain its most valuable data by viewing the planet close up at phase angles near 90 deg. The nonimaging planet-oriented experiments have various requirements for looking at the light side, dark side, and limb of the planet, and also various preferences for flyby altitude and speed.

Fields and particles experiments require low altitudes to detect the expected weak magnetic field and preferably should pass through the Sun occultation to sample the solar-wind wake behind Mercury.

The celestial-mechanics and radio-science experiment requires the spacecraft to pass through the Earth-occultation zone so that ef-

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fects of propagation through any Mercury atmosphere can be measured.

To satisfy all these requirements on a single trajectory is very difficult, if not impossible. From an imaging standpoint, the optimum lighting conditions occur on April 1. On this date the approach asymptote is normal to the Sun line, and the planet appears half-illuminated on the approach. However, the Sun and Earth occultation zones overlap little on this date. The earlier arrival dates have larger overlapping occultation zones (see page 56) and therefore do not require as small a final dispersion to assure passage through both.

The March 30 baseline arrival date allows a moderate occultation overlap and some 45% of the planet presented in sunlight to the approaching spacecraft. Fortunately, these arrival dates have the minimum available approach speeds of 10.5 km/sec.

The baseline trajectory is targeted for the occultation-overlap zone and a closest approach of 1000 km, as shown in diagrams on page 57.

Venus Flyby: As noted, choosing the Earth-launch and Mercury-arrival dates specifies the flyby conditions at Venus. The 1973 opportunity exhibits only a small variation in the Venus flyby conditions since the passage date is confined to a few days for trajectories of interest. Closest-approach altitude and duration of Earth occultation show the largest variations.

To illustrate typical passage conditions at Venus, three diagrams on page 58 show the planet and flyby trajectory from various vantage points: From the Earth, the spacecraft passing behind the planet; from the Sun (note, no Sun occultation); and from a point above the trajectory plane. The depictions here of Venus note the sites of several radar-identified surface features.[8]

Heliocentric Transfer: Earth-to-Mercury flights during the 1973 opportunity take typically 140-180 days. The spacecraft reaches Mercury near aphelion of its fairly eccentric orbit. In fact, it is this situation that makes the 1973 opportunity feasible with realizable launch energies.

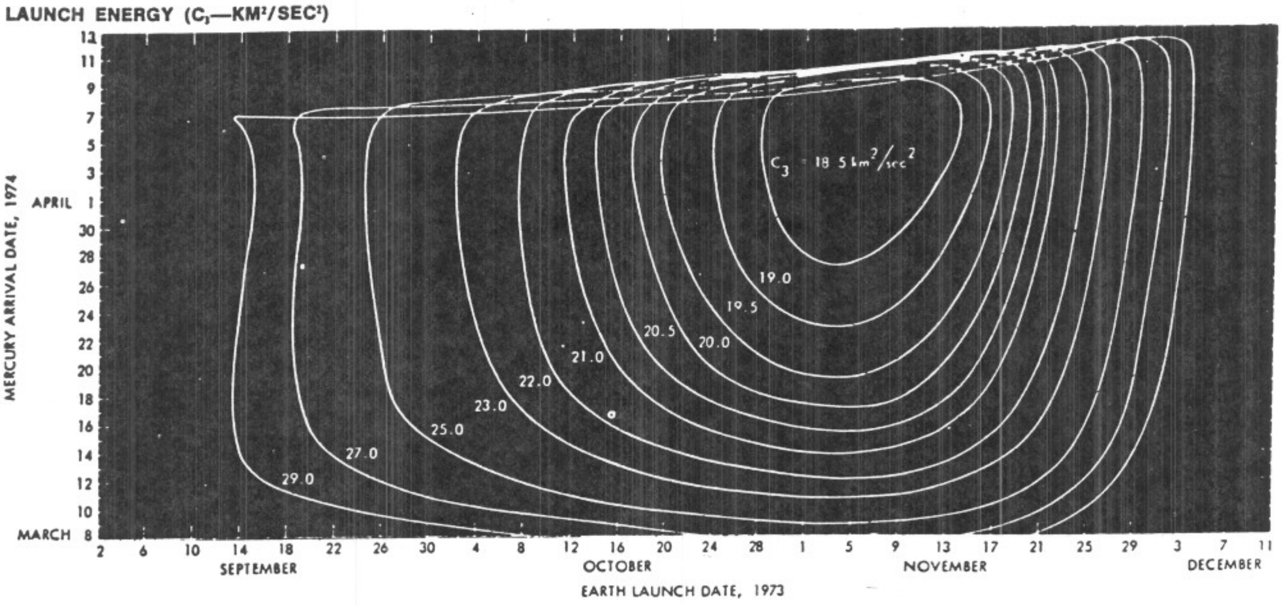
In an ecliptic-plane projection, top of chart on page 59 depicts the heliocentric transfer for a trajectory having an October 24, 1973 launch date and a March 30, 1974 Mercury-arrival date. At Mercury encounter the spacecraft has nearly reached its closest approach to the Sun. Perihelion passage occurs some five days after encounter at a distance of 0.46 AU. The spacecraft passes superior conjunction approximately 70 days after Mercury encounter. An edge view of the ecliptic in the bottom chart on page 59 shows the trajectory going above the plane, passing Venus near the planet's maximum celestial latitude, and then descending to Mercury below the ecliptic.

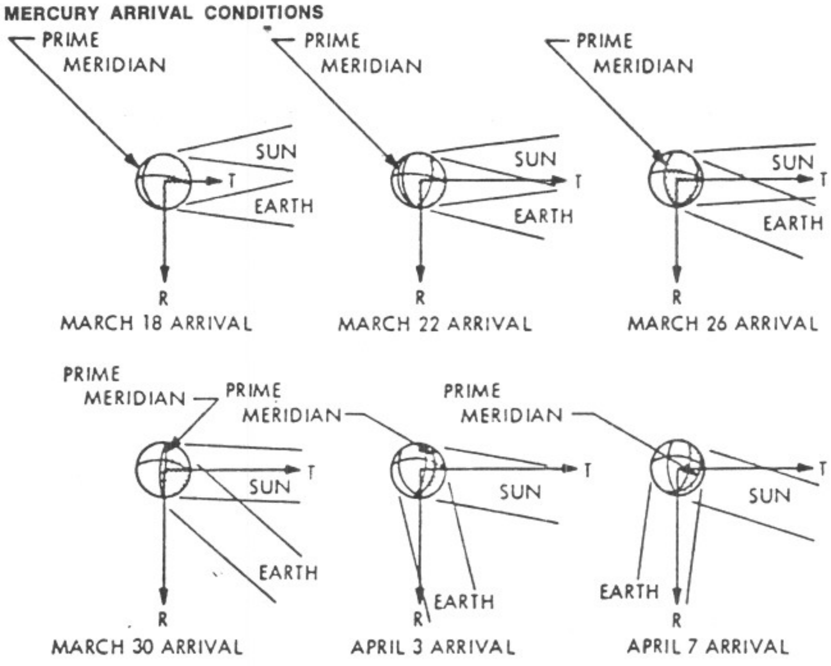
Return to Mercury: In 1970 Guiseppe Colombo of the Instituto di Meccanica Applicata alle Macchine, Padova, Italy (Professor Colombo discovered Mercury's 3-2 rotation-period and orbital-period synchronism in 1966),

MVM '73 SCIENCE EXPERIMENTS AND LEAD INVESTIGATORS

Experiment and Principal Investigator	Objectives
Television: B. C. Murray,* CalTech	Obtain imaging data on the surface of Mercury to map and identify major physiographic provinces, with special emphasis on the recognition of endogenic structures. Determine the spin-axis direction and investigate color differences on Mercury, and study clouds (especially in the ultraviolet), atmospheric structure, and general circulation at Venus.
Celestial Mechanics and Radio Science: H. T. Howard,* Stanford University	Detect and measure an ionosphere or atmosphere at Mercury and study the ionosphere and upper atmosphere at Venus. Also, determine the radius and mass of Mercury and search for gravitational harmonics at both planets.
Ultraviolet Spectrometer: A. L. Broadfoot, Kitt Peak Natl. Obser.	Detect the presence of an atmosphere at Mercury and identify some of its neutral constituents. Also, investigate certain neutral constituents of the upper atmosphere of Venus and map the celestial sphere in the H and He Lyman and during transit.
Infrared Radiometer: S. C. Chase Jr. Santa Barbara Research Center	Measure the infrared thermal radiation from the surface of Mercury between late afternoon and early morning, local time, and search for deviations from the average thermal behavior of the surface.
Plasma Science: H. S. Bridge, MIT	Determine the nature of the interaction of Mercury with the solar wind and from this derive conclusions about the planet. While in interplanetary space, study the plasma properties as a function of heliocentric distance.
Charged-Particle Telescope: J. A. Simpson, University of Chicago	Search for trapped radiation at Mercury and observe particles associated with a magnetotail and bow shock. Also, conduct studies bearing on solar and galactic origin and the modulation of quasi-steady fluxes of particles in interplanetary space.
Magnetometer: N. F. Ness, Goddard Space Flight Center	Study the solar-wind interaction with Mercury and Venus by means of vector magnetic field measurements. Determine whether a magnetic tail exists trailing behind Venus, and study the characteristics of interplanetary magnetic fields between 0.4 and 1.0 AU.

*Team leader.





pointed out that the spacecraft can return to Mercury after one complete revolution about the Sun. This unusual opportunity arises because the heliocentric orbital period of the Venus-Mercury leg of the trajectory is in the neighborhood of two Mercury orbital periods. Mercury makes one revolution about the Sun in 88 days. By selecting the proper aiming point at Mercury, the trajectory can be perturbed so that the spacecraft's heliocentric orbital period after encounter is exactly twice Mercury's period, thereby allowing the spacecraft to return to Mercury 176 days after the first flyby.

A direct Earth-Mercury trajectory does not present this return opportunity, since the heliocentric orbital period is much different from two Mercury orbital periods.

The chart on page 59 shows the March 30, 1974, Mercury aiming plane with the locus of aiming points which put the spacecraft on a returning trajectory. The set of aiming points depends on the date of launch. Fortunately, some aiming points in the dual-occultation region coincide with low launch-energy trajectories — i.e., trajectories with launch dates near November 5, 1973. Thus, the return to Mercury can be made without altering the baseline trajectory.

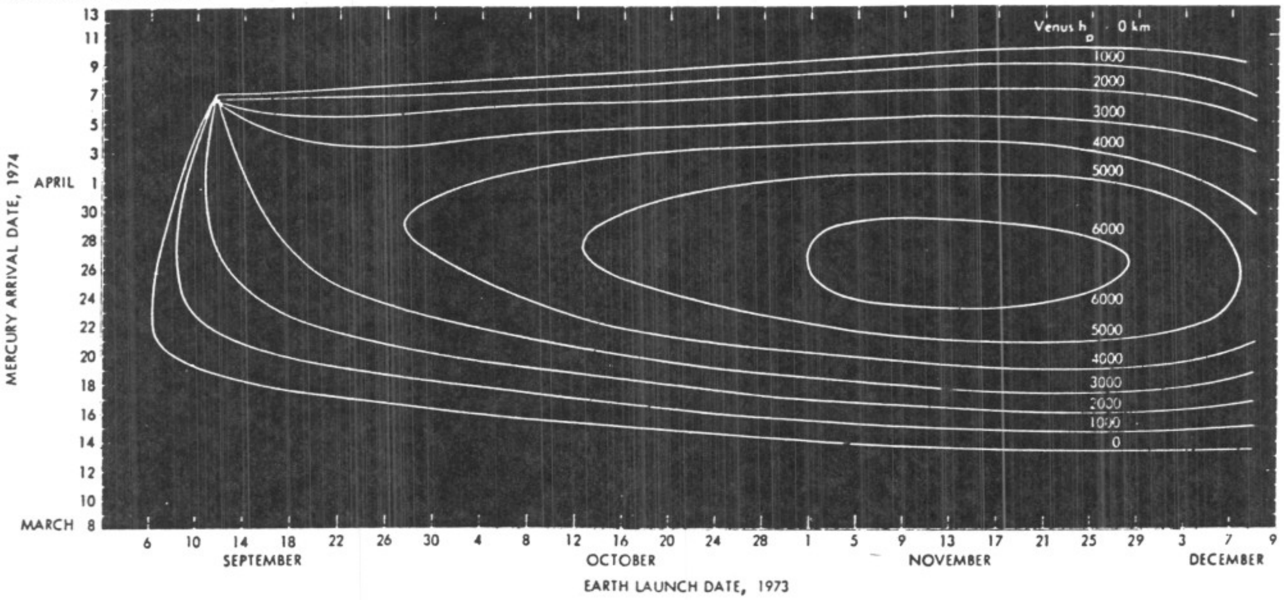
The aiming point for the second flyby is arbitrary. A polar flight might be desirable to view a different portion of the planet. The scientific objectives of the MVM '73 mission could be greatly enhanced, of course, by a second visit to Mercury.

Although the baseline mission design does not include the Mercury-return option, the possibility is under careful study.

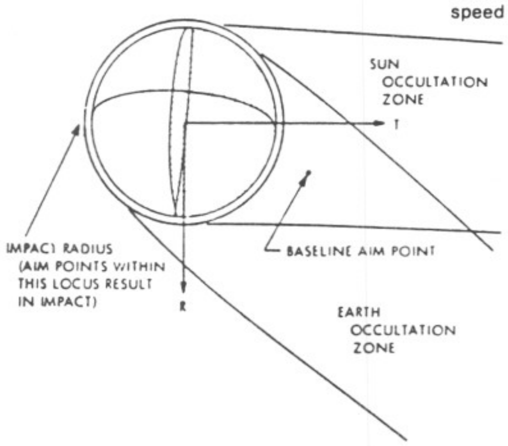
Navigation: The feasibility of the multi-planet mission hinges on accuracy of navigation at the intermediate planet. Sturms and Cutting demonstrated the practicality (propellant load reasonable in terms of navigational accuracy and trajectory-correction demands) of the swingby technique for the 1970 opportunity.[9] Sturms subsequently published a guidance analysis of the 1973 opportunity with similar conclusions.[6] Recent studies at JPL updating this analysis confirm its conclusions.

As in previous Mariner missions, the first trajectory-correction maneuver will be performed a few days after launch to remove launch-vehicle dispersions. Surveyor and MM'69 flight experience has shown

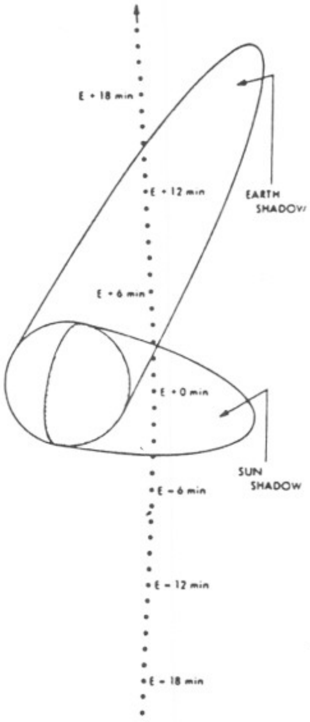
ALTITUDE AT VENUS



MERCURY FROM APPROACH ASYMPTOTE
March 30, 1974, arrival.



MERCURY-FLYBY TRAJECTORY PLANE
Dots mark 1-min intervals along the trajectory. Note small deflection of spacecraft's path, owing to high approach speed and small mass of the planet.



the exceptional accuracy of Atlas/Centaur. The rms dispersion at Venus following injection, but before a trajectory correction, should be 31,900 km. This means a single trajectory correction of only about 4.7 m/sec will bring the spacecraft within 400-500 km of the intended aiming point at Venus.

Aiming-point accuracy requirements at Venus, however, are exceedingly stringent: a l-km miss at Venus causes a 1000-km miss at Mercury, which, of course, must be corrected between Venus and Mercury.

To reduce the size of this post-Venus maneuver, the spacecraft must come as close as possible to the nominal aiming point at Venus. A second maneuver, of about 3.5 m/sec, will be performed a few days before Venus passage. The residual dispersion at Venus will then be almost entirely due to orbit-determination (OD) uncertainty at the time of this maneuver.

The level of OD accuracy depends on several factors: relative position of the Earth-based radio-tracking station, relation of the Earth's spin axis relative to the crust, charged-particle density between the station and the spacecraft, accuracy of Universal Time measurements, and unpredictable nongravitational forces on the spacecraft. (See the May 1970 A/A for a complete discussion of the problems in planetary navigation.)

Since it is necessary to know the position of the spacecraft relative to Venus, a highly accurate ephemeris for the planet is needed. Because of the two earlier flybys and radar-bounce experiments, knowledge of the ephemeris has improved dramatically over recent years, and rms ephemeris uncertainty is expected to be down to 1 km at the time the spacecraft reaches Venus.

Although optical observations can improve knowledge of the spacecraft's position relative to the planet (Kingsland[10] has shown the great advantage of this mode for the Grand Tour), the MVM'73 spacecraft will approach Venus from the dark side and the candidate optical instruments and imaging systems will have difficulty viewing objects close to the Sun. For this reason, there are no plans now to use optical measurements on the approach to Venus. They may be used at other times in the mission, but they are not being considered in the navigation strategy.

A preliminary analysis of radio-tracking accuracy for this mission indicates the final rms miss at Venus will be 25 km. This will necessitate a post-Venus maneuver of 4.8 m/sec (mean). The residual dispersion at Mercury after this maneuver comes primarily from execution errors.

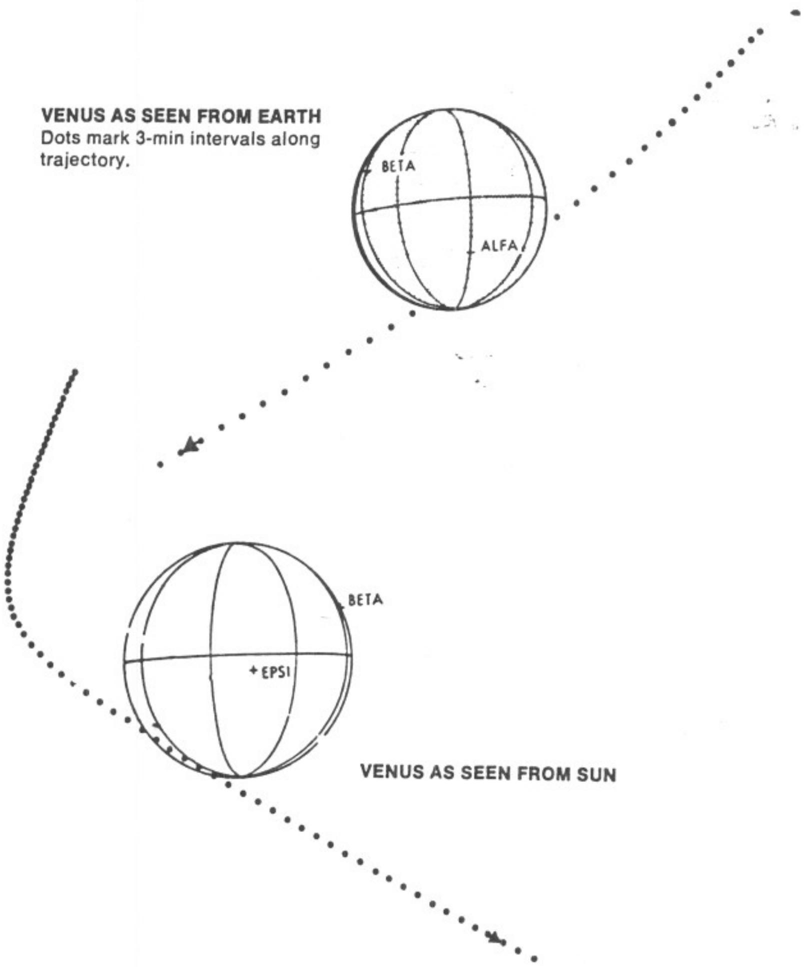
The chart on page 59 shows the 3-σ dispersion ellipse in the aiming plane centered on the nominal aiming point. This dispersion means a substantial probability that the spacecraft, following the third maneuver, will be on a course well away from the desired aiming point.

If this happens, a fourth maneuver will be performed. The same chart shows the small dispersion following this maneuver.

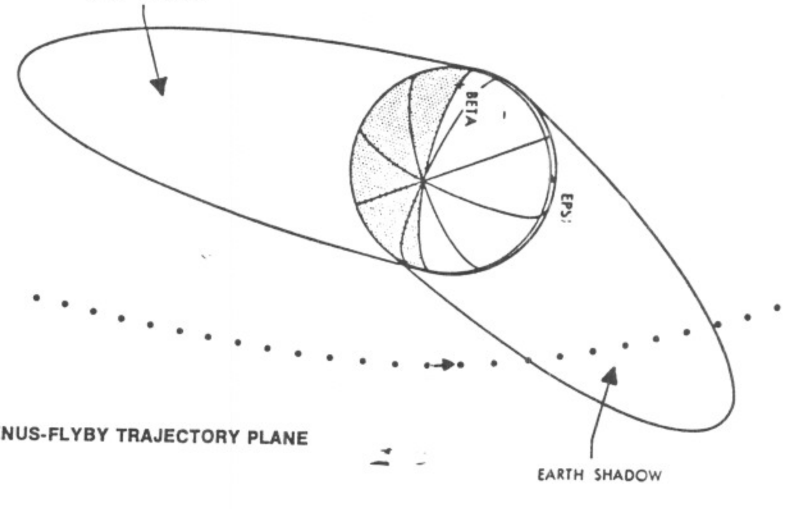
A thermal-control requirement —to tilt the solar panels away from the Sun when the spacecraft comes inside 0.63 AU — dictates the latest time the fourth maneuver can be made. The resultant shift in spacecraft center of mass prohibits maneuver in this configuration. So it must be performed within 23 days following Venus passage.

The rms magnitude of the fourth maneuver is extremely small, since it is performed well before Mercury arrival. If this maneuver is made, and if the aiming point falls near the locus for a return trajectory, there is a good chance that sufficient midcourse fuel will be left to bring the spacecraft back for a second Mercury flyby. It is expected that the maneuver velocity requirements for the return mission will be about 7-14 m/sec.

VENUS AS SEEN FROM EARTH
Dots mark 3-min intervals along trajectory.



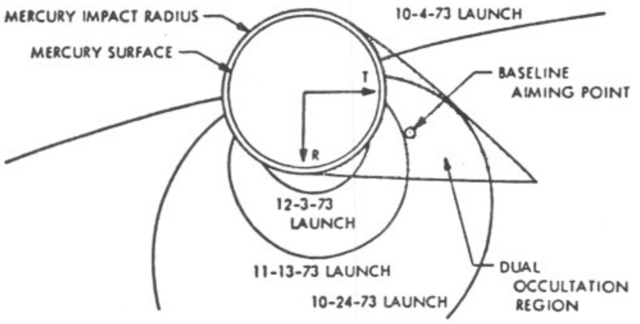
VENUS AS SEEN FROM SUN



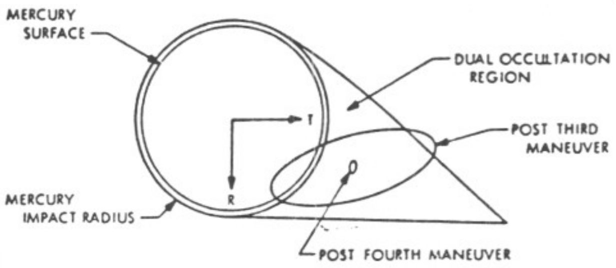
VENUS-FLYBY TRAJECTORY PLANE

TRAJECTORY CORRECTION MANEUVERS

Maneuver Time, days	Mean Size, m/sec	Purpose	Limitation	Implication
Launch + 10	4.7	Remove launch-vehicle dispersions.	Execution.	*rms* dispersion at Venus, 400-500 km.
Venus encounter − 3	3.5	Remove execution errors from first maneuver.	Orbit determination.	Third maneuver required.
Venus encounter + 3	4.8	Compensate for navigation errors at second maneuver.	Execution.	*rms* dispersion at Mercury of about 500 km.
Venus encounter + 15 to 23	0.2	Remove execution errors from third maneuver.	Orbit determination and execution.	Residual *rms* dispersion at Mercury of about 45 km.



Locus of return-trajectory aiming points for March 30, 1974, arrival.



Dispersion ellipses (3σ) on Mercury aiming plane for March 30, 1974, arrival. Scale: 1 in. equals 2000 km.

The table on page 58 summarizes the trajectory-correction maneuver requirements.

Concluding Remarks: Scientifically MVM '73 will greatly enhance our understanding of that strange planet closest to the Sun, Mercury. As a bonus, we will make a major new investigation of Venus.

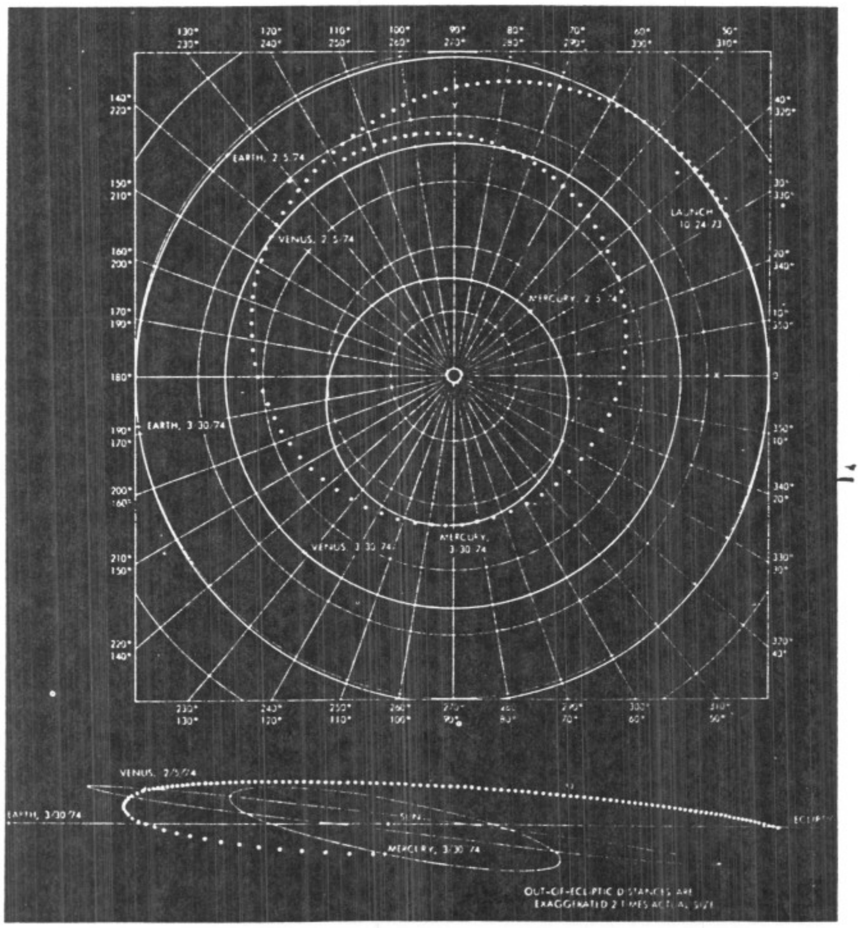
The mission has important implications, moreover, in terms of astrodynamics: For the first time this country will exploit the gravitational potential of a planet to significantly reduce launch requirements to achieve a final goal.

Furthermore, MVM '73 presents a navigation challenge unlike any previous mission's; the 1000-to-1 magnification in miss between Venus and Mercury calls for exceptional accuracy at the Venus passage.

Finally, the trajectory geometry may permit the spacecraft to return to Mercury for a second look.

Ten years ago, when we embarked on the first Venus mission, this would have been viewed as an amazing opportunity for space exploration indeed.

HELIOCENTRIC VIEWS OF TRANSFER TRAJECTORY
October 24, 1973, launch date. Dots on bottom chart mark two-day intervals.



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