Mariner Jupiter/Saturn 1977 Navigation Strategy

E. L. McKinley* and R. E. Van Allen†
Jet Propulsion Laboratory, Pasadena, Calif.

This paper presents selected navigational aspects of the Mariner Jupiter/Saturn 1977 mission. Emphasis is given to the trajectory correction strategy. In addition to science return and propellant costs, specific considerations affecting the strategy include a large number of candidate trajectories, relatively close satellite flybys, use of trajectory correction maneuvers for trajectory shaping, and the requirement for an optical data type to achieve precision satellite encounters. Finally, important error sources and mission constraints are identified, and their impact on the strategy is discussed.

I. Introduction

IN late August or early September of 1977, two Mariner spacecraft will be launched on trajectories possessing close encounters with the Jupiter and Saturn systems. Known as the Mariner Jupiter/Saturn 1977 (MJS77) Mission, it is the second Mariner mission designed to utilize the gravitational field of an intermediate planetary encounter to achieve a second planetary encounter. Mariner 10, with its successful flybys of Venus and Mercury, was the first. Missions of this type are characterized by a rather fortunate alignment of the target planets which allows the multiple encounters to be accomplished with relatively moderate launch energies and short flight times. On the other hand, missions of this type generally pose severe requirements on the navigation system required to accomplish those multiple encounters. For Mariner 10, the severe requirement reflected the large sensitivity of the Mercury encounter to errors in the Venus encounter, roughly a thousand kilometers to one. For MJS77, the requirement reflects the desire to achieve close flybys of the satellites of both Jupiter and Saturn. The mechanism by which these close flybys impose requirements on the navigation system will become clear from the discussion to follow.

This paper describes the trajectory correction maneuver (TCM) strategy required to meet the delivery accuracies which have been levied on the MJS77 navigation system. Included in the description are propellant costs, achieved delivery accuracies, and sensitivities to selected error sources.

Background

Mission Description

Each of the MJS77 spacecraft possesses a complement of ten science instruments. In addition, the radio system will be used to determine several of the physical parameters of members of the planetary systems. Much effort has been devoted to the selection of the planetary, satellite, and in the case of Saturn, ring encounter geometries which can be expected to yield the greatest return from those instruments.[1-3] At Jupiter, the desired flyby conditions include the following: 1) achieve close encounters with as many satellites as possible, in particular, with the Galilean satellites; 2) one of the spacecraft should penetrate the flux tube of a Galilean satellite and the second spacecraft should penetrate the wake of a Galilean satellite (Fig. 1). (A specific definition of the flux tube will be given later); 3) achieve Earth and Sun occultations of the spacecraft by Jupiter; 4) achieve a close Saturn encounter.

The desired Saturn encounter conditions are similar to those at Jupiter. They include the following: 1) achieve a close Titan flyby and as many additional close satellite flybys as is practicable; 2) achieve an occultation of the Earth and Sun by both Saturn and Titan; 3) achieve an occultation of the Earth by the rings. This occultation should occur sufficiently long after the Saturn occultation of Earth as to allow the ring occultation to be distinguished from Saturn effects. Specifically, the radio ray path height at ring occultation entry should be 5000 km above the surface of Saturn.

Generally, the Titan and ring related investigations are mutually exclusive. Consequently, each spacecraft will, nominally, be targeted to accomplish only one of those objectives. However, the Titan investigation is considered to be of such importance that the capability to retarget from a ring investigation aimpoint to a Titan aimpoint has been included in the mission and maneuver designs.

Since the selection of a Launch Date/Saturn Arrival Date (LD/SAD) implies a specific Juptier Arrival Date (JAD), trajectories which meet the requirement for close satellite flybys at both Jupiter and Saturn will not, in general, be ballistic. Post Jupiter, a small "deterministic ΔV" will be required to adjust the Jupiter to Saturn flight time. The affect of this ΔV on the total mission propellant requirements will be discussed later.

Standard Trajectories

Several trajectory pairs have been found which possess the characteristics just described. Of these, one particular pair (JSG and JSI) is preferred. (Recently, JSG has been deleted as a standard trajectory. In its place, a trajectory which provides the opportunity for a close Uranus flyby has been substituted.) Furthermore, analysis of several MJS trajectories has shown that this pair provides a representative test for a TCM strategy. In the interest of being concise, this paper will develop the TCM strategy for JSI, the interested reader being referred to Ref. 4 for a similar development for JSG. Using that strategy, the propellant requirements for virtually all trajectories may be inferred.

Navigation Requirements

The scientific investigations just described place a wide range of requirements on the navigation system. In order to deal effectively with these varying requirements, the concepts of Global and Local Trajectory Control were introduced in Ref. 5. Specifically, Global Trajectory Control consists of a set of activities designed to guide the spacecraft from Earth to Jupiter and from there to Saturn. Close encounters with selected satellites of each primary may also be a goal of this activity. Failure, at any time, to accomplish these activities could seriously compromise completion of the mission. Consequently, Global requirements must be accomplished using

Presented as Paper 75-1098 at the AIAA Guidance and Control Conference, Boston, Mass., Aug. 20-22, 1975; received Oct. 16, 1975; revision received Feb. 5, 1976. This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by NASA.

Index category: Spacecraft Navigation, Guidance, and Flight-Path Control Systems.

*Navigation Team Chief. Member AIAA.
†Maneuver Analyst. Member AIAA.

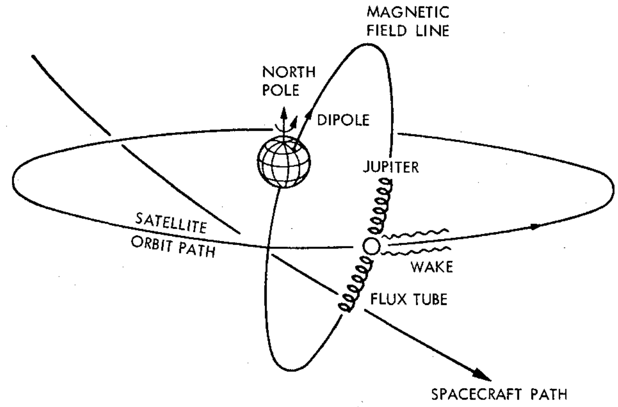


Fig. 1 Jupiter flux tube and wake diagram.

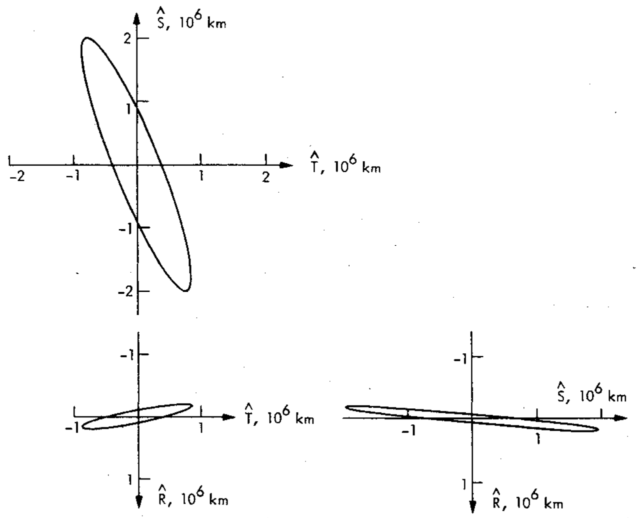


Fig. 2 Typical contour (one-sigma) of constant probability density function for MJS77 launch dispersions.

only the radio portion of the navigation system. Local Trajectory Control consists of a set of activities which will result in the acquisition of the full complement of science data. Failure to accomplish these activities, while highly undesirable, will not compromise completion of the mission. Use of the optical system for navigation purposes will be necessary if the Local requirements are to be met.

Since these two activities are of varying importance to mission success, different requirements have been placed on their being accomplished. Specifically, the probability of meeting Global and Local requirements has been established as 0.99 and 0.95, respectively. Table 1 shows the delivery accuracies, developed in Ref. 6, required to meet Global and Local Trajectory Control. The Global propellant requirement is 155 m/sec.

Maneuver Implementation and Execution Errors

The spacecraft implements a change to the trajectory by aligning the TCM thrusters in a predetermined inertial orientation followed by a timed burn of the necessary duration. Associated with the implementation of a TCM are execution errors. These errors are assumed to be zero mean, normally distributed random variables with 3σ dispersions shown in Table 2. The execution error model is that proposed in Ref. 7.

II. Trajectory Correction Strategy

The principal objectives of the trajectory correction strategy for MJS are the elimination of the launch vehicle and TCM execution errors as a major contributor to the final delivery uncertainty and the minimization of the TCM propellant requirements. The first objective is, of course, a statement of the desire to deliver the spacecraft to a target relative position with the smallest possible delivery error consistent with the delivery accuracy requirements. The second objective is a recognition of the fact that some candidate trajectories possess propellant requirements exceeding the present Global requirement (see Sec. III.). Further, as we shall see in this section, meeting the second objective offers the opportunity to improve the quality of the Jupiter satellite encounter. It is interesting to note that the two objectives are not necessarily mutually exclusive. Specifically, accomplishing the first objective on the Earth-Jupiter leg helps achieve the second objective.

Table 1 Delivery accuracy requirements (3σ) for Global and Local trajectory control

Control type	At Jupiter	At Saturn
Global	1500 km satellite relative	4000 km planet relative
Local	600 km satellite relative	600 km satellite relative

Table 2 Trajectory correction maneuver execution errors for the MJS77 spacecraft (3σ)

Source	Magnitude
Shutoff error, %	9.0
Resolution error, m/sec	0.2
Pointing error (per axis), mrad	20.0
Autopilot error, m/sec	0.2

Earth-Jupiter Strategy

Accomplishing the objectives given previously on the Earth-Jupiter leg of the JSI mission will nominally require four TCMs to meet the Global and Local Delivery requirements. In summary, this result reflects the following: 1) relatively large launch injection errors; 2) the relatively late improvement in the knowledge of the spacecraft state with respect to the target satellite (Io); 3) the large change, following the first TCM, in the sensitivity of time of flight to velocity perturbations; 4) the errors associated with the execution of a TCM.

The manner in which these items necessitate the required number of maneuvers to accomplish the objectives stated above will now be given. Figure 2 shows the one sigma contour of the probability density function for the launch vehicle injection errors. Three views are shown corresponding to projections into the three coordinate planes $\hat{S}-\hat{T}$, $\hat{T}-\hat{R}$ and $\hat{R}-\hat{S}$ (Fig. 3). These unusually large dispersions are due, primarily, to the Propulsion Module (PM), the solid propellant final stage of the launch vehicle.

A simple comparison of the delivery accuracy requirements discussed previously (Table 1) with the large launch dispersions (Fig. 2) is sufficient argument for implementing at least one TCM. The actual placement of that maneuver turns out not to be extremely time critical. Figure 4 shows why this is true. This figure plots, as a function of time from injection, the magnitude (λ_1, λ_2, λ_3,) of the gradient vectors, $\bar{\lambda}_1$, $\bar{\lambda}_2$, $\bar{\lambda}_3$, where $\dot{X}$, $\dot{Y}$, $\dot{Z}$ are a reference set of cartesian axes. The superscript dot denotes time differentiation. Note the dramatic changes in TCM capability which occur within approximately one day of injection. Since it is not practicable to determine the specific launch error and implement a correction within this time frame, small adjustments of a few days in the first maneuver epoch are acceptable. Consequently, the first maneuver epoch has been scheduled for Injection plus 10 days.

Velocity increment requirements for this first TCM are shown by Fig. 5. These requirements were derived from a Monte Carlo simulation of the JSI trajectory. However, since the launch errors are expected to be similar for any trajectory

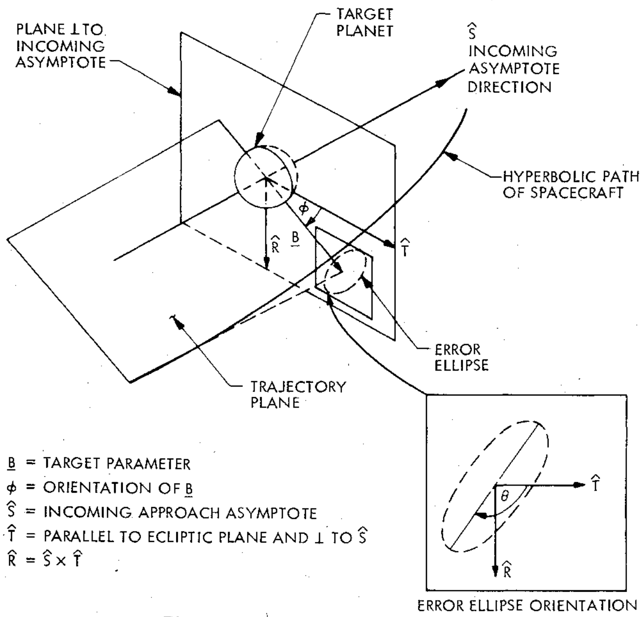


Fig. 3 ***B*-plane coordinate system.**

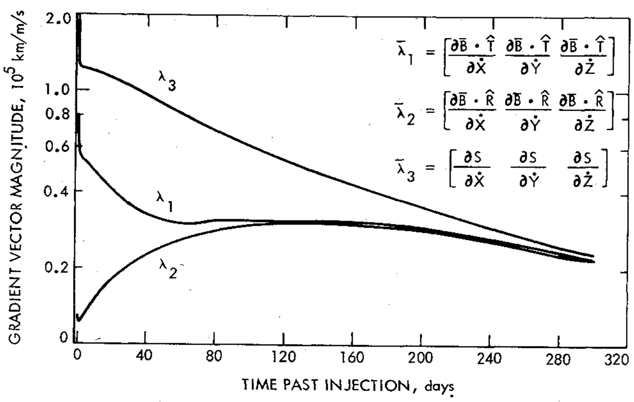


Fig. 4 Magnitudes of the gradient vectors as a function of time past the injection epoch: JSI trajectory.

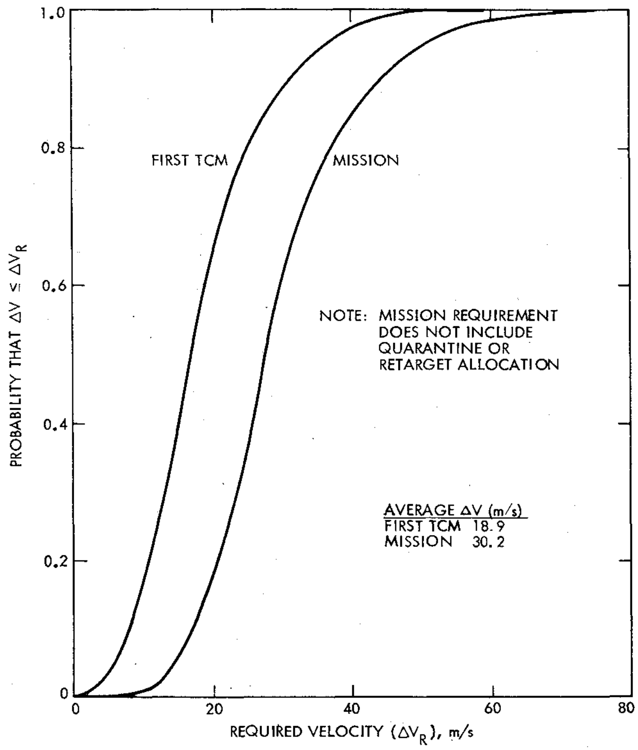


Fig. 5 Velocity increment requirements for the first TCM on the Earth-Jupiter leg of JSI and for a mission with no deterministic ΔV.

in the available LD/SAD space, Fig. 5 can be considered typical for the MJS mission.

Figure 5 shows that the expected size of the first TCM is approximately 18.9 m/sec. For a maneuver of this size, Table 3 implies that the principal execution error will be the shutoff error. Consequently, typical 1-σ post maneuver errors will be 3% of those shown by Fig. 2. Again, in light of the encounter requirements, delivery errors of this size are unacceptable. Evidently, a second TCM is required; however, a relatively simple argument can be constructed which shows that one more TCM will not, in general, achieve the required delivery accuracy.

We have seen that, following the first TCM, the 1-σ Jupiter relative errors will be between 3×10^4 and 6×10^4 km. Denoting this error by ϵ_{B_1} and denoting the partial of B with respect to velocity at the second maneuver epoch by $\lambda(t_2)$ (cf, Fig. 4) then the second maneuver velocity increment, ΔV_2, may be approximated by

$$\Delta V_2 = \epsilon_{B_1}/\lambda(t_2) \tag{1}$$

For this velocity increment, the 1-σ post maneuver error, ϵ_{B_2}, due to execution errors (cf Table 3 and Ref. 7), is given by

$$\epsilon_{B_2} = \lambda(t_2)[(0.03\Delta V_2)^2 + (0.067)^2]^{1/2} \tag{2}$$

or, substituting for ΔV_2

$$\epsilon_{B_2} = \{(0.03\epsilon_{B_1})^2 + [0.067\lambda(t_2)]^2\}^{1/2} \tag{3}$$

Clearly, $\epsilon_{B_2} \geq 900$ km, i.e., the 3-σ error following a second TCM will exceed the 1500 km delivery requirement (Table 1). Therefore, at least three TCMs will be required.

The preceding analysis has ignored uncertainties in the knowledge of the position and velocity of the spacecraft at the moment we decide to execute the TCM. The justification for this reflects the relatively small size of these uncertainties (on the order of 10^3 km) compared to the launch and post-first and post-second maneuver errors. For subsequent maneuvers, however, these knowledge errors become significant, even though they decrease in size as the spacecraft approaches Jupiter. Furthermore, the preceding analysis assumed a scalar representation for the error model of the spacecraft when, in fact, a three dimensional vector representation is required. This assumption is reasonable when attempting to bound the propellant costs and delivery errors of a single maneuver, but is usually unreliable for analyzing multiple maneuvers. Thus, to establish the requirement for a fourth maneuver, results of Monte Carlo simulations of three and four maneuver strategies were used.

Table 3 Average propellant costs for the final two TCMs of a three maneuver strategy.[a]

Second TCM epoch, days before Jupiter encounter	300	200	100	50
Average second TCM ΔV, m/sec	1.5	2.2	4.6	9.5
Average third TCM ΔV, m/sec	12.3	9.8	8.1	7.6
Total of TCMs two and three, m/sec	13.8	12.0	12.7	17.1
Excess cost over a four TCM strategy, m/sec	9.3	7.5	8.2	12.6

[a]The third maneuver epoch is EJ – 4 days. The average cost of the final three TCMs of a four TCM strategy is 4.5 m/sec.

Table 4 Maneuver strategy and velocity requirements for the Earth-Jupiter leg of JSI

TCM no.	Epoch[a] days	Mean ΔV m/sec	ΔV_{99} m/sec
1	I+10	18.9	45.1
2	EJ−300	1.5	7.9
3	EJ−30	1.4	3.9
4	EJ−4	1.6	4.1
Leg	–	23.4	53.8

[a] I ≡ injection, EJ ≡ Jupiter encounter.

Table 3 shows the average propellant costs for the second, third, and second plus third maneuvers of a three maneuver strategy as a function of the second TCM epoch. The first and third maneuvers are simulated for Injection plus ten days and Jupiter encounter minus four days (EJ−4d), respectively. Also shown, line 4, is the incremental cost of the final two maneuvers of the three maneuver strategy over the costs for the final three maneuvers of a four maneuver strategy. The cost of the first maneuver for both the three and four maneuver strategies is, of course, the same.

Lines one and two of Table 4 demonstrate the relationship given by Eqs. (1) and (3), respectively. Since ϵ_{B_I} is a function only of the initial launch vehicle injection error and the first TCM execution error, both of which may be considered constant, Eq. (1) shows that the second TCM velocity increment is inversely proportional to $\lambda(t_2)$. Figure 4 shows the degradation in the maneuver capability for each encounter parameter as a function of time past injection. Not shown, however, is the relatively uniform decrease in these parameters with time, beginning at approximately 300 days prior to Jupiter encounter. This correlation with time implies, and line 1 of Table 3 confirms, that the second maneuver velocity increment will vary inversely with the time remaining before Jupiter encounter. On the other hand, Eq. (3) expresses, and line 2 of Table 3 confirms the following: 1) for late second maneuvers, the second maneuver execution error is dominated by the shutoff error and the third maneuver velocity increment asymptotically approaches a constant value. Column 4 of Table 3 shows this constant to be approximately 7.6 m/sec; 2) for early second maneuvers, the resolution and autopilot errors dominate the second maneuver execution errors. Consequently, the third maneuver increases in size.

Line 3 of Table 3 summarizes the effect of different second maneuver epochs. These data show that the total propellant requirement for a three maneuver strategy possesses a minimum. With the third maneuver epoch at EJ−4 days, this minimum occurs for a second maneuver epoch near EJ−150 days. It is easily shown, however, that when the third maneuver epoch is EJ−6 days the minimum occurs for a second maneuver epoch at EJ−200 days. Furthermore, in the latter case, the difference in the average propellant requirements between the three and four maneuver strategies is reduced from 7.3 to 4.2 m/sec. Obviously, then, further reductions in this difference could be achieved by performing the third maneuver even earlier. Unfortunately, for JSI the Io relative delivery requirements cannot be met for final pre-encounter maneuvers earlier than approximately EJ−5 days.

Studies in Ref. 6 have shown that the knowledge of the spacecraft ephemeris relative to Io does not decrease below 300 km (1-σ) until approximately EJ−11 days. As pointed out by F. M. Sturms, Jr., of the Jet Propulsion Laboratory, this is due to the fact that for these trajectories the Io encounter occurs after Jupiter periapsis and, more importantly, it occurs near the point where the Jupiter relative approach asymptote crosses the orbit plane of Io. This particular geometry results in a substantial defocusing of Jupiter relative knowledge errors when they are mapped to the B-plane of Io. The third TCM execution errors experience the same effect. Since the final delivery uncertainty consists of knowledge plus execution errors, the Io delivery requirement can be met with a three TCM strategy only if the final pre-encounter maneuver is performed no earlier than EJ−5 days. Although we have reached this conclusion by considering the Local Requirements for Io, the conclusion is essentially identical for meeting the Global requirements. With this constraint on the final maneuver epoch, the propellant costs are unacceptable. Thus, a four maneuver strategy is required.

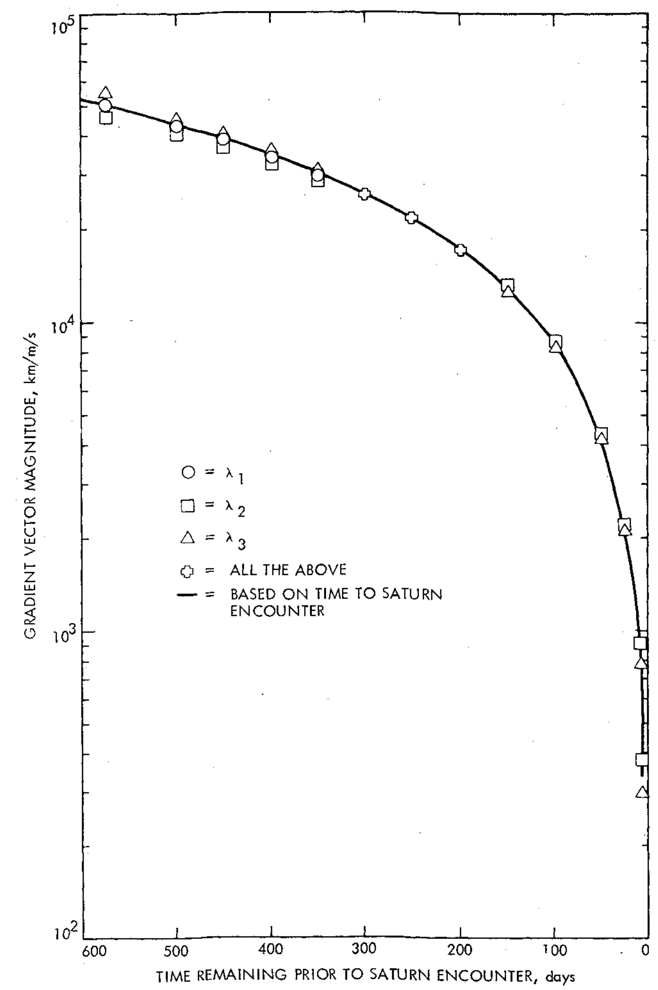


Fig. 6 Magnitude of maneuver capability gradient vectors: Jupiter-Saturn leg of JSI.

In conclusion, to meet the two objectives of the Earth-Jupiter TCM strategy, four maneuvers will nominally be required for JSI. The timing of the maneuvers is shown by Table 4. Also given are the average velocity increment and the velocity increment corresponding to the 0.99 probability level requirements (ΔV_{99}) for each TCM and for the Earth-Jupiter leg. These results were obtained from a Monte Carlo simulation of the indicated strategy.

Jupiter-Saturn Strategy

The objectives of the maneuver strategy on the Jupiter-Saturn leg of the mission are essentially the same as for the Earth-Jupiter leg. However, the development of the maneuver strategy for the Jupiter-Saturn leg is considerably simpler than was the case for the Earth-Jupiter leg. This is due, primarily, to the fact that the post-Jupiter heliocentric trajectory is hyperbolic, with a relatively small central angle transfer, approximately 55° (from a true anomaly of approximately 15° to a true anomaly of 70°). For this transfer, one would expect that the trajectory of the spacecraft could be approximated by rectilinear motion. In that event, the sensitivity of the Saturn encounter parameters to velocity perturbations would be nearly proportional to the time remaining from the epoch of interest to Saturn encounter (referred to as "time-to-go"). Furthermore, one would expect that the gradient vectors, which represent the maneuver capability (Fig. 4) would be mutually perpendicular. Figure 6 shows that from a practical point of view, the first of these conjectures is correct. The second conjecture, although not shown, has also been verified. The simplifications in the development of the maneuver strategy which result from these characteristics will become apparent as the strategy for JSI is developed.

As with the Earth-Jupiter leg, the JSI mission will require four TCMs to meet the Local Delivery requirements. (The Global Delivery requirements can be met with just three TCMs. However, since the Local requirements are more important, scientifically, the maneuver strategy is developed to satisfy the Local requirements.) As will be shown below, the four maneuvers are required because of the following: 1) the relatively large deterministic ΔV; 2) the relatively late improvement in the knowledge of the spacecraft ephemeris with respect to the target satellite (Dione); 3) the errors associated with the execution of a TCM.

The sources of the errors which necessitate maneuvers on the Jupiter-Saturn leg are the delivery dispersions relative to Jupiter and its satellites and, typically more important, the deterministic ΔV designed into the nominal trajectory for purposes of achieving close satellite flybys at both Jupiter and Saturn. As a result of the relatively large satellite flyby distances, the propellant requirement resulting from the 1-σ delivery dispersions, is less than 5 m/sec. On the other hand, the deterministic ΔV for JSI is 26 m/sec. Since the sensitivity of the Saturn B-plane parameters to velocity perturbations is approximately 50,500 km/m/sec, it is clear that at least one TCM is required.

The magnitude of the deterministic ΔV implies that this first TCM should be performed as soon as possible following the Jupiter encounter. In order not to interfere with the science activities during the Jupiter encounter, this maneuver has nominally been scheduled for EJ + 40 days. It is interesting to note, however, that the timing of this maneuver is not time critical. This may be seen by recalling that the maneuver capability is proportional to the "time-to-go" (t_g). Denoting the proportionality constant by k (k = 86.4 km/m/sec/day), then from Eq. (1), with $\lambda = kt_g$, we have

$$\partial \Delta V / \partial t_g = -\Delta V / t_g \tag{4}$$

For JSI, EJ + 40 days corresponds to $t_g \approx 585$ days, so that $\partial \Delta V / \partial t_g = -0.044$ m/sec/day.

The size of the first post-Jupiter maneuver implies that the shutoff error will dominate the execution errors. Consequently, the 1-σ post-maneuver B-plane error (ϵ_{B_1}) will be approximately 3.94×10^4 km. Furthermore, since the first maneuver is executed for the purpose of removing the deterministic ΔV, the post-maneuver distribution of errors may be approximated as a univariant distribution.

By repeating an analysis scenario for the Jupiter-Saturn leg similar to that given for the Earth-Jupiter leg, it can be shown that, from a propellant point of view, for a three maneuver strategy to be competitive with a four maneuver strategy, the third maneuver of the three maneuver strategy must be placed at approximately ES − 7 days or earlier. However, the Dione closest approach occurs after Saturn periapsis, thereby paralleling the Io encounter geometry at Jupiter. As was the case at Io, the improvement in the knowledge of the ephemeris of the spacecraft relative to Dione precludes executing the final pre-encounter TCM prior to approximately ES − 4 days. This increases the predicted average cost for the final pre-encounter TCM of a three TCM strategy to approximately 10 m/sec when the optimal second maneuver epoch is used. As a result, the average cost of the final two maneuvers of a three TCM strategy exceeds the costs for the final three maneuvers of a four maneuver strategy by approximately 6 m/sec. For this reason, a four maneuver strategy is nominally required for JSI. As might be expected, for the four maneuver strategy, the selection of the maneuver epochs for the second and third TCMs is not particularly critical. They have tentatively been scheduled for ES − 300 days and ES − 30 days, respectively.

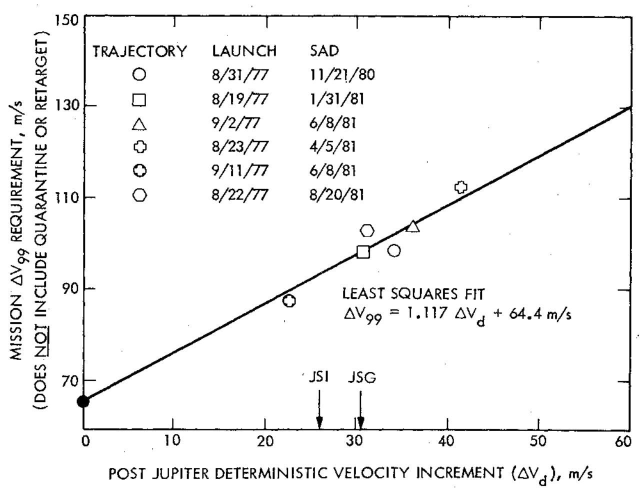


Fig. 7 Mission ΔV_{99} as a function of the post-Jupiter deterministic ΔV. (These data do not include PQ or retarget requirements.)

In conclusion, to meet the two objectives of the maneuver strategy on the Jupiter-Saturn leg, JSI will normally require four maneuvers. Table 5 summarizes the velocity requirements for the Jupiter-Saturn leg of JSI.

III. Propellant Cost Summary

In this section, the propellant costs for the MJS77 mission are summarized. Included are brief discussions of the costs associated with the Retargeting Maneuver and with Planetary Quarantine. As noted previously, JSI is a representative trajectory for the purpose of Maneuver Strategy development. The strategy developed for JSI has been used in Monte Carlo simulations of several other candidate trajectories. Figure 7 shows that the mission propellant requirements vary almost linearly with the deterministic ΔV. The 11.7% penalty in mission ΔV_{99} associated with each one m/sec increase in the deterministic ΔV is due, primarily, to the shutoff execution error.

Figure 5 shows the cumulative distribution for an MJS mission with zero deterministic ΔV. Comparison of this curve with similar curves for other trajectories has shown that the shape is essentially independent of the deterministic ΔV. Consequently, Figs. 5 and 7 may be used to estimate the propellant requirements for any probability level given the deterministic ΔV.

Each MJS spacecraft has been allocated propellant equivalent to approximately 25 m/sec for the purpose of providing some capability to retarget the nominal trajectory from an aimpoint which gives a ring occultation at Saturn to an aimpoint which gives a close (approximately 27,000 km) Titan flyby. This reflects the keen interest with which the science investigators view the Titan related investigations. A 25 m/sec allocation was selected on the basis of preserving the

Table 5 Maneuver strategy and velocity requirements for the Jupiter-Saturn leg of JSI

TCM no.	Epoch[a] days	Mean ΔV m/sec	ΔV_{99} m/sec
1	EJ + 40	26.3	31.7
2	ES − 3000	1.4	4.2
3	ES − 30	1.5	3.1
4	ES − 4	3.2	6.5
Leg	–	32.3	39.6

[a] EJ ≡ Jupiter encounter ES ≡ Saturn encounter.

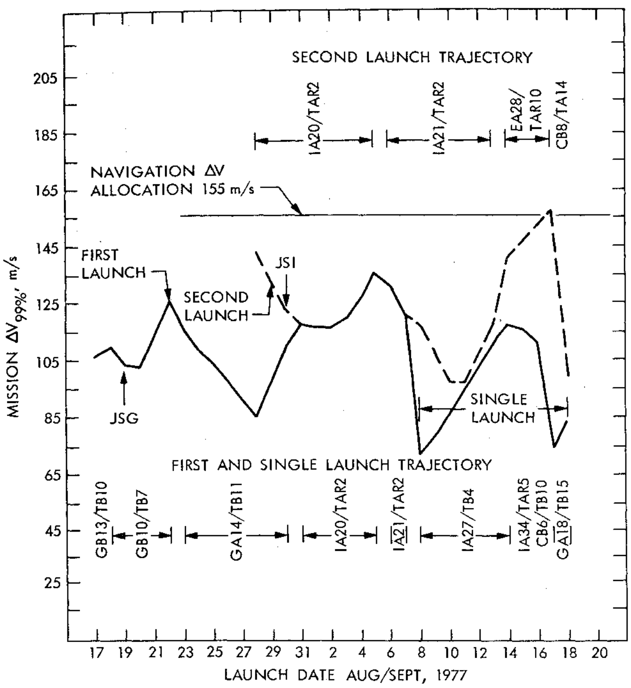


Fig. 8 Propellant requirement vs launch date for a candidate launch strategy. Satellite abbreviations are Ganymede (G), Io (I), Callisto (C), Titan (T), and Europa (E). Other abbreviations are rings of Saturn (R), after primary periapsis (A), and before primary periapsis (B). Numbers refer to relative opportunity. (Note: The data do not include a 5 m/sec contingency which is presently allocated to navigation.)

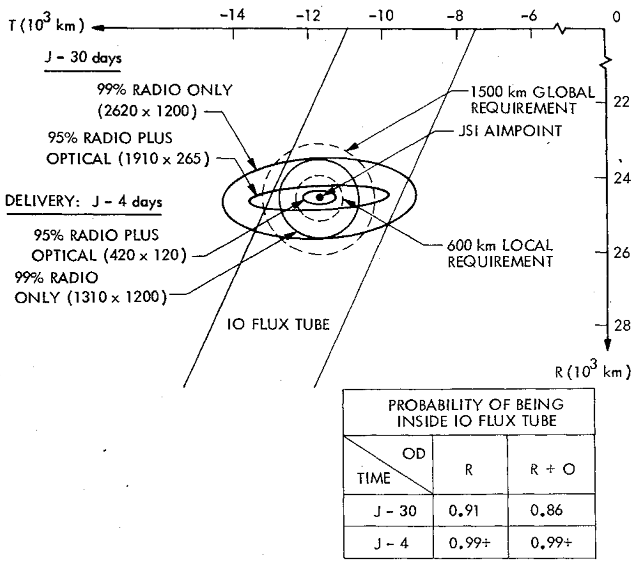


Fig. 9 Io relative trajectory dispersions for a four maneuver strategy on the Earth-Jupiter leg: JSI trajectory.

retargeting capability to an Epoch of ES − 60 days. However, if control of the Saturn arrival time is not required, a condition which results in giving up close flybys of Mimas, Tethys, and Dione, then the allocation is adequate for retargeting maneuvers as late as ES − 20 days. From the point of view of the required propellant budget, the 25 m/sec is simply added to requirements necessary to meet all other mission objectives. Of course, this is necessary only for those trajectories which are not targeted to Titan.

Each spacecraft comprising the MJS77 mission is required to satisfy the planetary and satellite quarantine (PQ) requirements established by NASA. Namely, the allowable probability of contaminating Jupiter, Saturn or any of their

Table 6 Summary of the probability of contaminating the specified body for each spacecraft and the propellant costs associated with meeting the requirements

Body	Probability of contamination capability[a] $\times 10^{-5}$	Required bias m/sec
Jupiter	0.4	0.0
Satellite (Jupiter)	2.0	0.0
Saturn	2.0	0.0
Satellite (Saturn)	30.0	5.0

[a]Computed for the case of no bias in the aimpoint.

Table 7 Incremental propellant requirements and associated *B*-plane bias necessary to satisfy planetary quarantine when retargeting the JSI spacecraft from a ring occultation aimpoint to a close (27,000 km) Titan flyby[a]

Maneuver and epoch	Bias ΔV m/sec	Bias distance (Titan relative) km
Retarget EJ + 70d	1.5	70000[b]
Second ES − 300d	3.0	1100[c]
Third ES − 30d	0.5	0[c]

[a]Assumed probability of contaminating Titan given impact is 1.0. [b]Bias shown is introduced by this maneuver in order to satisfy PQ. [c]Bias shown is that which remains following the indicated maneuver.

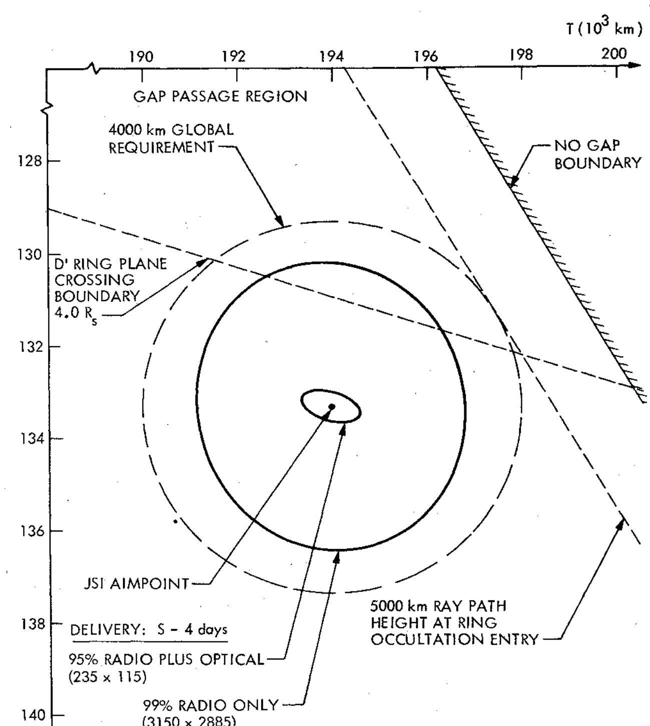
satellites must not exceed 6.4×10^{-5}. For navigation, the PQ constraints translate into requirements for TCM strategies and aimpoint selection which, when all important sources of potential contamination are considered, satisfy

$$P_{C/I} \sum_k P_{I_k} Q_{k+} \leq P_C \tag{5}$$

where $P_C = 6.4 \times 10^{-5}$, $P_{C/I}$ = probability of contamination given impact of the spacecraft with one of the planets or satellites, P_{I_k} = the probability of the spacecraft impacting one of the planets or satellites following the kth TCM, and Q_{k+} = probability that an attempted maneuver, subsequent to the kth, will fail.

Table 6 gives the estimated propellant requirements for complying with this constraint. This table shows that, with the exception of Saturn's satellites (specifically, Titan), the quarantine constraints do not impose a requirement to bias any of the planet or satellite aimpoints. For Jupiter and its satellites as well as for Saturn, the combination of relatively large flyby distances, and maneuver reliability results in small probabilities of contamination.

The circumstance which can be expected to require that the Titan aimpoint be biased accompanies the event where the spacecraft is retargeted from a ring experiment to a close Titan flyby. For this case, the relatively large change in the aimpoints necessary to accomplish the transition from a ring to a Titan investigation result in execution errors which require moderately large biases to satisfy PQ. Table 7 illustrates the scenario for JSI when the retarget maneuver is performed at EJ + 70 days. The first row shows that when the retarget maneuver is executed, it is necessary to bias the Titan aimpoint by 70,000 km. This adds approximately 1.5 m/sec to the retarget ΔV. The next two TCMs are performed at their nominal epochs (cf. Table 5). However, the execution errors associated with executing the nominal second maneuver preclude removing the total bias introduced by the retarget



PROBABILITY OF RAY PATH HEIGHT ≤ 5000 km AT RING OCCULTATION ENTRY		
TIME \ OD	R	R + O
S - 4	0.99+	0.99+

Fig. 10 Saturn relative trajectory dispersions for the JSI trajectory.

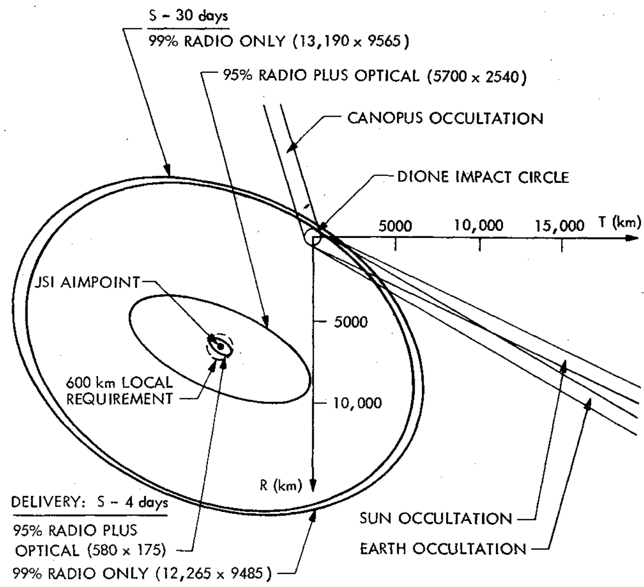


Fig. 11 Dione relative trajectory dispersions for the JSI trajectory.

maneuver. The portion remaining is removed by the nominal third maneuver. We see that the total increment in propellant costs is 5 m/sec. For purposes of specifying mission propellant requirements, this cost, like the retargeting allocation, is added to the requirements necessary to meet all other mission objectives.

Using the preceding results, the propellant requirements for trajectories which comprise a candidate launch strategy developed in Ref. 8 have been determined (Fig. 8). This figure shows the mission ΔV_{99} for the first spacecraft and for the second spacecraft for each day in the launch period. The ten day period between the first and second launches reflects the time required to refurbish the launch pad. Thus, a failure to launch the first spacecraft by September 8 will, for the purposes of this paper, result in a one spacecraft mission. The code assigned to each trajectory identifies selected features of that trajectory. For example, GB13/TB10 refers to the thirteenth opportunity in the launch period to encounter Ganymede Before Jupiter encounter and the tenth opportunity to encounter Titan Before Saturn encounter. In this code, only the satellite encounter of primary interest is given. We note that only one trajectory, EA28/TAR10, is predicted to exceed the propellant allocation of 155 m/sec.

Delivery Accuracies

This section presents the delivery accuracy to several of the target aiming zones for JSI. Since the maneuver strategy has been designed to minimize the contribution of launch vehicle errors, uncertainties resulting from removal of biases, and maneuver execution uncertainties, the delivery, to first order, is comprised of knowledge errors at the time of the final pre-encounter maneuver. The execution errors have been included, however.

Jupiter Delivery

Figure 9 shows the delivery to the Io flux tube following the third and fourth maneuvers on the Earth-Jupiter leg. The flux tube width is assumed to be equal to the diameter of Io (3240 km) and to extend for a distance equal to approximately twenty times the radius of Io (32,400 km). The delivery following the third maneuver does not meet the Global or the Local Delivery requirement. However, the probability of achieving a flux tube passage following the third maneuver is still reasonably high. Furthermore, although it is not shown, the delivery is sufficiently accurate to result in Sun and Earth occultations of the spacecraft by Jupiter.

Saturn Delivery

Figure 10 shows the Saturn relative delivery for JSI. Clearly, the Global delivery requirement is met. Furthermore, the minimum ray path height above the surface of Saturn prior to entering ring occultation is achieved. Figure 11 illustrates the Dione relative delivery for the JSI trajectory. This figure provides a dramatic representation of the importance of the optical data to the satellite delivery. In particular, it demonstrates the inability of the radiometric data to detect, in a timely manner, the uncertainties in the ephemeris of the satellite. Even though the Local Delivery requirement is met, the Dione flyby has no specified aim zone. The nominal flyby point simply corresponds to the Saturn flyby point selected to meet the requirements for the ring investigation.

Conclusions

This paper has presented the Trajectory Correction Maneuver Strategy, propellant costs and achieved delivery accuracies for the MJS77 mission. In summary, we have shown that four maneuvers are required for those legs of the mission where the primary satellite flyby occurs after planetary closest approach. (Note: Ref. 4 has shown that for trajectories where the satellite closest approach precedes the closest approach with the primary, only three maneuvers may be required. This result is also applicable to the Earth-Jupiter leg of the mission. For both the three and four maneuver scenarios, the TCMs are adjusted so that the propellant requirements are approximately the same.)

The propellant requirement necessary to accomplish the required encounters has been shown to be proportional to the post-Jupiter encounter deterministic ΔV. The propellant required to satisfy Planetary Quarantine on the Jupiter-Saturn leg has been shown to be less than 5 m/sec, corresponding to those cases where the spacecraft is retargeted from a ring to a Titan investigation. Biasing for Planetary Quarantine is not required on the Earth-Jupiter leg. Using the relationship between propellant requirement and deterministic ΔV, the requirements for Planetary Quarantine and the propellant allocated for retargeting, the propellant requirements for a candidate launch strategy have been given. With one exception, the propellant requirements for this strategy are less than 155 m/sec, the Global propellant requirement.

References

[1]Bourke, R. D., Miles, R. F., Penzo, P. A., Van Dillen, S. L., and Wallace, R. A., "Mariner Jupiter-Saturn 1977 Preliminary Mission Design," AIAA Paper 72-943, Palo Alto, Calif., 1972.

[2]Beerer, J. G., Penzo, P. A., and Wallace, R. A., "Computation and Analysis of Satellite Opportunities for the Mariner Jupiter/Saturn 1977 Mission," AAS/AIAA Astrodynamics Conference, Vail, Colo., 1973.

[3]Penzo, P. A., "Science Objectives and the Mariner Jupiter/Saturn 1977 Mission Design," AIAA Paper 74-780, Anaheim, Calif., 1974.

[4]McKinley, E. L., and Van Allen, R. E., "Mariner Jupiter/Saturn 1977 Navigation Strategy," AIAA Paper 75-1098, Boston, Mass., 1975.

[5]Curkendall, D. W., "Navigation System Design for the Mariner Jupiter/Saturn Mission," AIAA Paper 73-838, Key Biscayne, Fla., 1973.

[6]Curkendall, D. W., et al., "Mariner Jupiter/Saturn 1977 Navigation Plan," PD618-115 (Internal Document) Jet Propulsion Lab., Pasadena, Calif., Dec., 1974.

[7]Gates, C. R., "A Simplified Model of Mid-Course Maneuver Execution Errors," TR No. 32-504, Jet Propulsion Lab., Pasadena, Calif., Oct. 1963.

[8]Wallace, R. A., "Preliminary MJS77 Launch Strategy," EM 392-117 (Internal Document), Jet Propulsion Lab., Pasadena, Calif., July, 1974.