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by John W. Young and Margery E. Hannah

Langley Research Center
Hampton, Va. 23665

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16. Abstract

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SUMMARY

A study has been made of a method for providing more frequent launch opportunities for multiple-planet Grand Tour type missions to the outer solar system. A Saturn-Jupiter flyby sequence was used in the analysis to initiate the mission instead of the normal Jupiter-Saturn sequence.

The Saturn-first approach is shown to yield several new launch opportunities following the 1980 cutoff date for Jupiter-first missions. Results are given for various two-planet, three-planet, and four-planet Jupiter-first and Saturn-first missions. A unique five-planet Saturn-first mission and a Saturn-Jupiter flyby which returns to Earth are also discussed. Mission performance is evaluated for each flyby technique by comparing Saturn-first and Jupiter-first missions with respect to launch energy requirements, available launch windows, planetary encounter conditions, and total mission times.

INTRODUCTION

A rare alinement of outer solar system planets in the late 1970's has resulted in considerable interest in the so-called Grand Tour mission. In brief, this mission involves sequential flybys of outer solar system planets such that the gravity perturbation during close approach to one planet is used to alter spacecraft heliocentric energy and momentum so that the vehicle will proceed to the next planet. This technique allows a single vehicle to perform multiple flybys, resulting in lower launch energies and trip times than normally required for direct missions to the individual planets.

The name "Grand Tour" was originally applied to a ballistic trajectory from Earth to Jupiter followed by flybys of Saturn, Uranus, and Neptune (ref. 1). Recently the Grand Tour name has also been given to a number of three-planet opportunities that occur in the late 1970's. Numerous studies relating to these missions have been made (for example, refs. 1 to 6). These studies, which considered missions where the vehicle always proceeds to a planet at a greater heliocentric radius, have shown that launch opportunities exist from about 1976 to 1980 with repeat cycles determined by the mutual synodic periods between the planets involved. Due to the large synodic periods of the outer planets, the time interval between similar alinements is long. For example, as was shown in reference 7, three-planet missions now under consideration can not be repeated for a minimum of about 100 years, while the repeat cycle for four-planet missions is about 179 years. These long delays between possible launches place severe limitations on outer-planet exploration.

The objective of the present study is to investigate a method for providing more frequent launch opportunities for Grand Tour missions. The approach used was to consider a flyby sequence other than the standard one whereby flybys are made to planets of increasing orbital radius. The method used involved a flyby sequence of Saturn followed by Jupiter, plus various combinations of the other outer planets. Since the Saturn-first approach must be initiated by a Saturn-Jupiter sequence, only missions involving Saturn and Jupiter in combination with other outer planets are included in the report.

Previous results using the Saturn-first approach are given in reference 8. Additional results are given in the present report to show how the Saturn-first approach yields several new launch opportunities for Grand Tour missions following the 1980 cutoff date for Jupiter-first missions. Mission profiles for these new opportunities are compared with those occurring in the 1976 to 1980 period. Mission performance is evaluated for both techniques by giving comparisons between launch energy requirements, available launch windows, and total mission times. Planetary-encounter-orbit characteristics are analyzed with respect to such quantities as flyby distances, lighting conditions, and vehicle occultation times.

METHOD

Physical Model and Assumptions

Planetary orbits.- A three-dimensional two-body model was used to define planet ephemerides. In this model the planets moved along inclined ellipses and heliocentric position coordinates, and velocities were computed from the mean Keplerian elements. The assumed physical constants and the mean Keplerian elements of the planets were taken from reference 9. This analytical representation of planet ephemerides was found to be convenient for computational purposes.

Spacecraft trajectories.- Spacecraft trajectories were determined using a two-body patched-conic approximation. Thus, the spacecraft was either in a Keplerian heliocentric orbit, or a hyperbolic planet-centered orbit. With this model, the calculation of each multiple-planet flyby mission involved a sequence of two-body problems.

Planets were assumed to be gravitationally spherically symmetric, and the sphere of influence of a planet was assumed to be small in comparison with interplanetary distances. Therefore, in the computation of heliocentric spacecraft trajectories, the planet and its sphere of influence were approximated by a point mass on the planetary orbit. It was further assumed that the spacecraft could exert no propulsive forces during any part of the mission.

The Keplerian two-body equations and flyby dynamics used in the analysis are readily available in the literature (see, for example, refs. 10 and 11), and no detailed description will be given in the present report. Various phases of a flyby mission will, however, be discussed in order to introduce the terminology to be used and to define trajectory parameters of interest. The symbols are defined in the appendix.

Transfer Geometry

Insertion parameters.- The insertion trajectory was initiated at exit from the sphere of influence of the Earth. Variables used to define the trajectory were hyperbolic excess launch velocity (V_H) and the heliocentric flight-path angle (γ_I) and inclination (i_I) of the injection trajectory. The insertion date must also be given in order to establish the heliocentric position coordinates and the velocity vector of the Earth at insertion. Having specified these quantities, the heliocentric insertion velocity (V_I) can be determined.

Pre-encounter trajectory.- The heliocentric transfer between Earth and another planet is referred to as a pre-encounter trajectory. The orbital elements of this trajectory are determined from the heliocentric insertion conditions (V_I, γ_I, i_I) and the radial distance from the vehicle to the Sun at insertion (r_I). The vehicle-Sun distance r_I was assumed to be the same as the Earth-Sun radial distance at insertion.

Having specified the orbital elements of the insertion trajectory at Earth, the pre-encounter orbit from Earth to the encounter planet is defined. Thus, heliocentric approach conditions $(V_A, \gamma_A, i_A, r_A)$ at the encounter planet can be determined. Determination of the heliocentric distance from the spacecraft to the Sun at encounter (r_A) merits some discussion. As previously stated, planets were assumed to be point masses with their spheres of influences shrunk to zero. Therefore, for heliocentric transfer orbits, the trajectories go from the center of one planet to the center of the next planet. Thus, r_A is equal to the distance from the encounter planet to the Sun (r_P). Since the planets move along ellipses, r_P is continually changing with time and must be determined in an iterative fashion. Details of this iterative procedure are given in the section entitled "Computational Procedure."

Flyby orbit.- Although heliocentric trajectories were assumed to go from the center of one planet to the center of another, during the gravity-turn or flyby maneuver at a planet, consideration must be given to the gravitational field of the planet and the passage distance. The geometry of a flyby orbit is shown in figure 1. Heliocentric approach and departure conditions are denoted, respectively, by subscripts A and D. Corresponding planet referenced conditions are denoted by lowercase subscripts a, d, and p. As shown in figure 1, the vehicle approaches along one asymptote of the encounter hyperbola, is deflected through an angle δ, and departs along the other asymptote. Asymptotic approach and departure speeds (V_a, V_d) are equal, with the deflection angle being a function of flyby distance (r_p), asymptotic approach speed, and the gravitational field of the planet. The encounter causes changes in heliocentric direction and velocity as illustrated in figure 1. The heliocentric-velocity change occurs because the asymptotic approach and departure velocity vectors are different in direction, although equal in magnitude. Heliocentric departure velocity may be greater or less than approach velocity, depending on the encounter conditions.

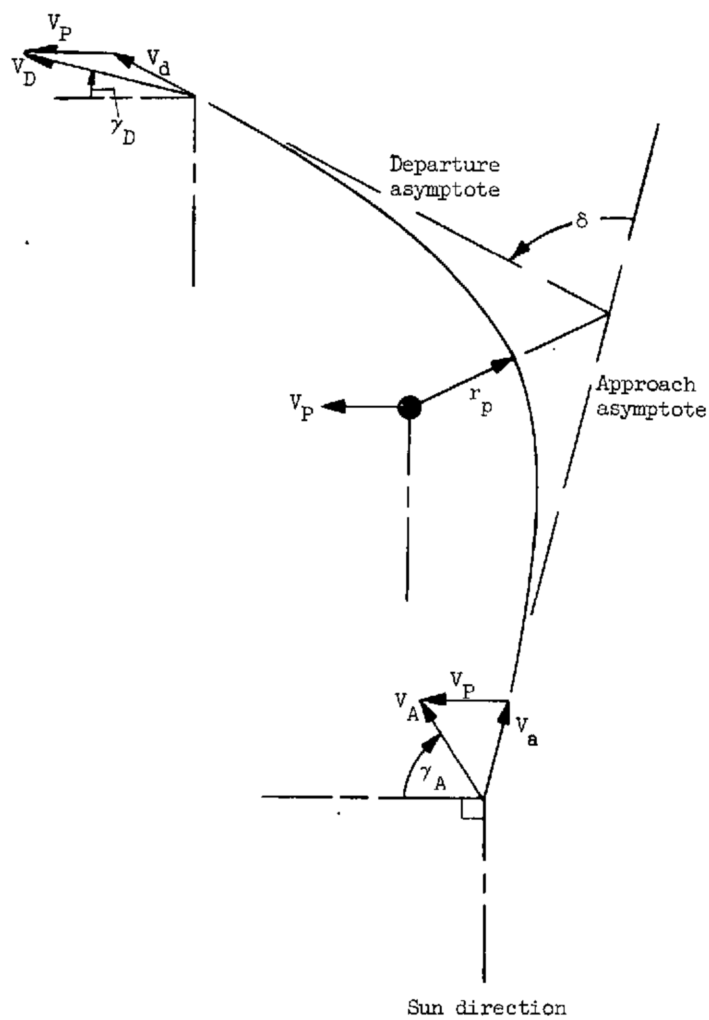


Figure 1.- Geometry of encounter orbit.

One additional variable, the inclination of the plane of motion of the flyby orbit with respect to the equatorial plane of the planet $\left(i_P\right)$, is required to fully specify an encounter (see ref. 11). In the current analysis, the equatorial plane is taken to be coincident with the orbital plane of the planet. Thus, the inclination of the flyby orbit determines the out-of-plane component of the departure velocity of the vehicle. For example, consider a vehicle orbiting in the ecliptic which performs a flyby of a planet that is also orbiting in the ecliptic. If an equatorial flyby is made, then assuming perfect guidance and no planetary gravity anomalies, the post-encounter orbit will also be in the ecliptic. However, if the flyby is inclined to the equatorial plane, an out-of-ecliptic post-encounter trajectory will result.

The encounter of figure 1 corresponds to an equatorial flyby in which the direction of rotation of the flyby orbit is the same as the direction of revolution of the planet around the Sun. This type of flyby will be referred to as a direct encounter and generally increases the heliocentric energy of the vehicle. An alternate equatorial encounter involves a flyby in which the rotation is opposite to the direction of revolution of the planet. This encounter, which generally reduces heliocentric energy, will be referred to as a retrograde encounter.

Post-encounter trajectory.- The elements of the post-encounter trajectory can be determined from the heliocentric departure conditions $\left(V_D,\gamma_D,i_D,r_D\right)$, where $r_D = r_A = r_P$. The transfer orbit to the next planet can be calculated using these elements. The post-encounter trajectory from one planet then becomes the pre-encounter trajectory to the next planet, and the previously described procedure is repeated at each succeeding flyby planet.

Computational Procedure

The computation of any multiple-planet flyby requires that numerous mission parameters be specified such that all mission constraints are satisfied. Various procedures can be used to find those combinations of variables which will meet required constraints. The procedure used in the present report involved an application of nonlinear programing theory. A constrained minimization technique was used which was capable of iteratively determining mission variables, subject to mission constraints, while minimizing some function of the variables. The algorithm used in carying out the constrained minimization was developed by Kelley and others (refs. 12 to 14). It is based on Davidon's method of conjugate gradients, as modified by Fletcher and Powell. The computer program was obtained from Johnson of reference 12 and was modified for use in the present study.

Since the minimization algorithm is discussed thoroughly in the cited references, no technical description will be given. However, the general manner in which the technique was applied in the current study will be outlined. A hypothetical two-planet mission will be discussed with regards to mission variables, mission constraints, and implementation of the constrained minimization technique.

Consider a two-planet mission which makes successive flybys of Jupiter and Saturn. Four variables, hyperbolic excess velocity (V_H), heliocentric flight-path angle at insertion (γ_I), heliocentric inclination angle at insertion (i_I), and the insertion date, are required to specify the insertion trajectory. These variables can not be chosen arbitrarily since the vehicle orbit must intersect the orbit of Jupiter such that an encounter is possible. The flyby orbit at Jupiter must then be adjusted such that the vehicle proceeds to an encounter at Saturn. Mission variables at Jupiter include the distance of closest approach to the planet (r_p) and the inclination of the flyby orbit to the equatorial plane of Jupiter (i_p). Therefore, for this Jupiter-Saturn mission, a total of six variables are involved.

The nonlinear programing algorithm uses an iterative procedure which requires an initial estimate for the mission variables. Also, mission constraints must be specified and a payoff or minimization function must be defined. The payoff function was taken to be total mission time. That is, the mission was to be achieved in the shortest possible time subject to the constraints. Due to long mission times involved in multiple-planet flybys, the minimum time requirement seemed to be a reasonable criterion for comparison of various Grand Tour missions.

Having specified the flyby sequence, mission constraints, and initial values for the mission variables, a computer solution of the Jupiter-Saturn flyby would proceed as follows: In order to calculate the transfer orbit from Earth to Jupiter, the distance from Jupiter to the Sun at the time of encounter must be known. Since the Jupiter-Sun distance is continually changing with time, its value at encounter, a function of the insertion date and the Earth-Jupiter transfer time, is not known in advance. Therefore, an estimated Jupiter-Sun distance at encounter is used. The Earth-Jupiter transfer trajectory is then calculated, and the transfer time is found. The insertion date and transfer time are then used to calculate the true Jupiter-Sun distance at encounter based on the planet ephemeris model discussed in the section on planetary orbits. This computed Jupiter-Sun distance normally will not agree with the estimated distance. Therefore, a new estimate is made and the previously discussed procedure is repeated until the calculated and estimated Jupiter-Sun distances are the same. Once agreement is obtained, the flyby at Jupiter and the Jupiter-Saturn transfer are computed. Since the true Saturn-Sun distance at encounter is not known in advance, the previously described procedure for obtaining the Jupiter-Sun distance is repeated to determine the Saturn-Sun distance.

Having calculated this initial estimate for a Jupiter-Saturn flyby, various mission constraints are now checked. In general, the calculated longitudes and latitudes of the vehicle at Jupiter and Saturn will not agree with the corresponding ephemerides of Jupiter and Saturn at encounter. Thus, mission variables must be adjusted such that the desired flybys can be achieved. The nonlinear programing algorithm iteratively determines required values for the mission variables such that the desired ephemeris constraints are met.

Other constraints of a practical nature must also be considered during the iterative solution. For example, the insertion variables must be constrained such that aphelion of the insertion trajectory is at least as great as the Jupiter-Sun distance at encounter with Jupiter. Likewise, the flyby at Jupiter must produce a post-encounter trajectory which reaches the orbit of Saturn. Also, the distance of closest approach to Jupiter must be constrained to be above the atmosphere of Jupiter. The computer algorithm includes all of these constraint considerations in arriving at a final determination of the mission variables. Thus, having specified the planet sequence, mission constraints, and an initial estimate for the trajectory variables, the digital program determines those combinations of variables which satisfy all constraints while minimizing total trip time.

ANALYSIS

Results are given for multiple-outer-planet missions involving various planet flyby sequences. For purposes of identification, these missions will be denoted as "Jupiter-first" or "Saturn-first" type flybys. In order to facilitate specific comparisons between overall mission performance, the general characteristics of typical Jupiter-first and Saturn-first trajectories will be examined.

Mission Profiles

Jupiter-first mission.- A typical four-planet, Jupiter-first mission is shown in figure 2. The Jupiter-first mission, which has been analyzed extensively in the literature (refs. 1 to 7) and occurs in the 1976 to 1980 launch period, is initiated by a flyby of Jupiter followed by flybys of other planets of increasing orbital radius. As is generally the case for Jupiter-first missions, all flybys are direct as shown in figure 2. That is, the direction of rotation of the flyby orbit is the same as the direction of revolution of the planets around the Sun. Direct flybys normally result in an increase in heliocentric velocity; and since the mission of figure 2 involves an inner ring pass at Saturn, a relatively short trip time of about 9 years can be achieved.

Saturn-first mission.- A typical Saturn-first mission involving the same four planets as the Jupiter-first mission of figure 2 and with an insertion date in 1992 is shown in figure 3. Note that, with the exception of Jupiter, all encounters for the Saturn-first mission are retrograde in that the direction of rotation of the flyby orbit is opposite to the direction

Insertion Date - 9/6/77
V_H - 10.75 km/sec
Mission Time - 8.96 yr

Planet	Flyby Date	r_p,radii
Jupiter	1/23/79	4.00
Saturn	8/13/80	1.07
Uranus	12/22/83	1.71
Neptune	8/21/86	-

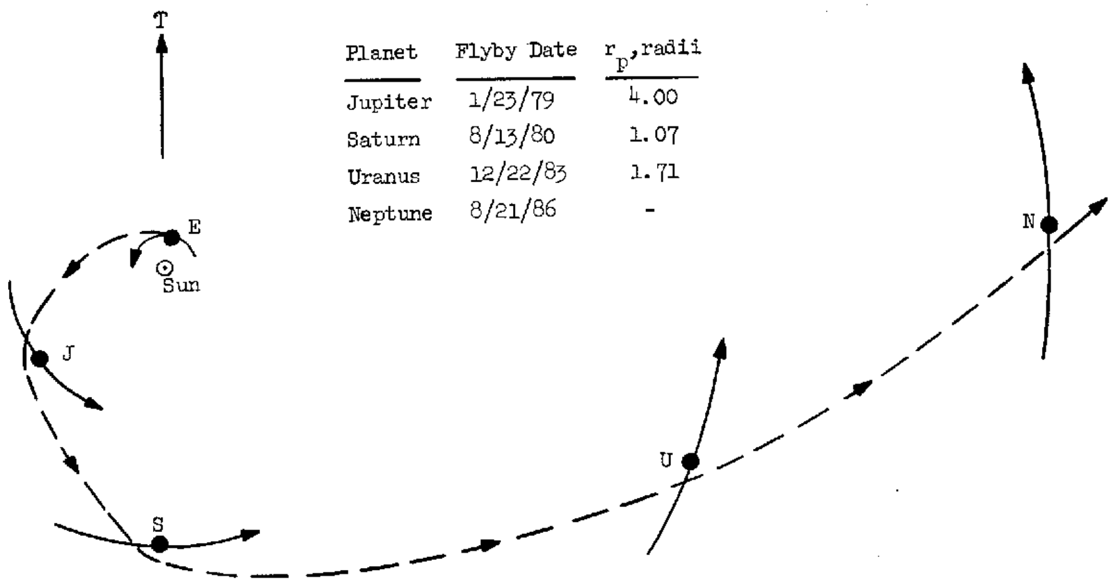


Figure 2.- Typical four-planet, Jupiter-first mission.

Insertion Date - 4/10/92
V_H - 12.8 km/sec
Mission Time - 12.3 yr

Planet	Flyby Date	r_p,radii
Saturn	9/17/94	1.07
Jupiter	5/5/97	1.01
Uranus	1/7/01	2.61
Neptune	8/1/04	-

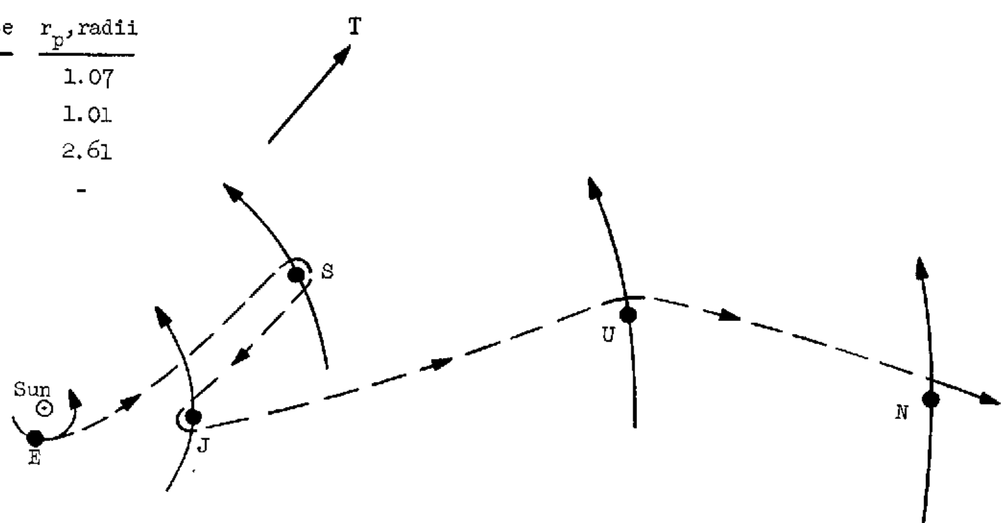


Figure 3.- Typical four-planet, Saturn-first mission.

of revolution of the planets around the Sun. Since retrograde maneuvers normally reduce heliocentric velocity and since the space between Saturn and Jupiter must be traversed three times, the Saturn-first mission of figure 3 requires about 3.3 more years than the Jupiter-first mission of figure 2.

A vectorial representation of the flyby maneuvers in the Saturn-first mission of figure 3 is given in figure 4. Shown are heliocentric and planet referenced approach and

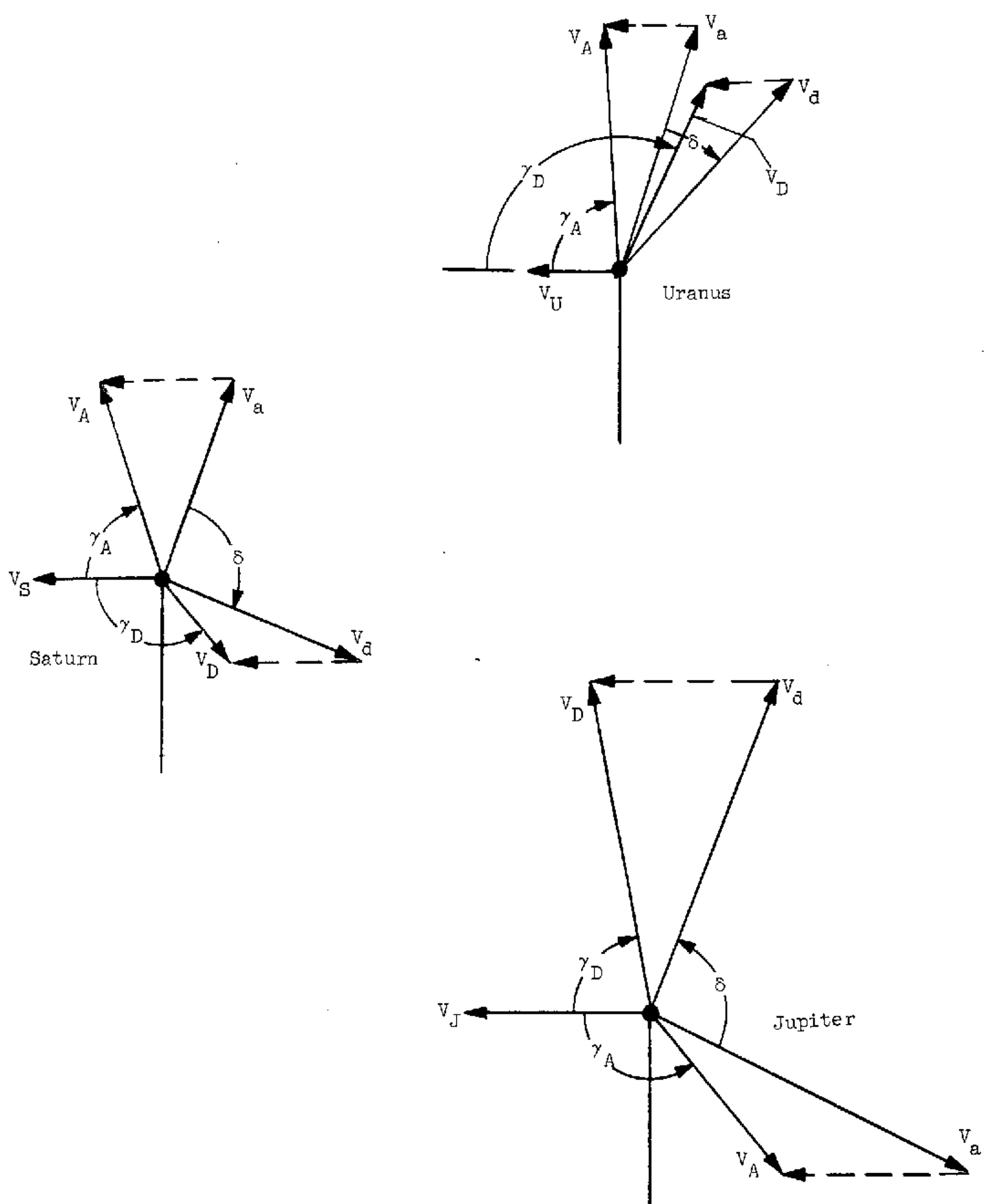


Figure 4.- Encounter conditions for Saturn-first mission of figure 3.

departure velocities at Saturn, Jupiter, and Uranus. The retrograde encounter at Saturn causes a large reduction in heliocentric velocity $(V_A = 14.8 \text{ km/sec}; \; V_D = 7.8 \text{ km/sec})$; and, as shown in figure 4, the resulting departure flight-path angle (γ_D) is greater than 90^o in magnitude. Thus, the Saturn-Jupiter (S-J) heliocentric transfer is in a direction opposite to the planet orbits (see fig. 3). The high asymptotic approach velocity $(V_a = 25.5 \text{ km/sec})$ and gravity-turn angle (δ) at Jupiter combine to yield a substantial increase in heliocentric velocity $(V_A = 15.1 \text{ km/sec}; \; V_D = 23.8 \text{ km/sec})$. The retrograde encounter at Uranus causes some reduction in heliocentric velocity $(V_A = 17.5 \text{ km/sec}; \; V_D = 14.8 \text{ km/sec})$ and the Uranus-Neptune (U-N) heliocentric transfer is in a direction opposite to the planet orbits.

Saturn-first missions of the type shown in figure 3 are possible in the late 1980, early 1990 launch period. Additional Saturn-first missions in this time period, as well as in the post-2000 period are also possible by making a retrograde flyby at Jupiter. A typical mission of this type is illustrated in figure 5. Shown is a three-planet mission involving Saturn, Jupiter, and Uranus, which has a launch date in 2011. Note that the post-Jupiter transfer angle for this mission is large in comparison with those which perform direct maneuver at Jupiter (fig. 3). However, due to the large departure velocity from Jupiter, overall trip times will be shown to be comparable with those for missions in the 1990 launch period.

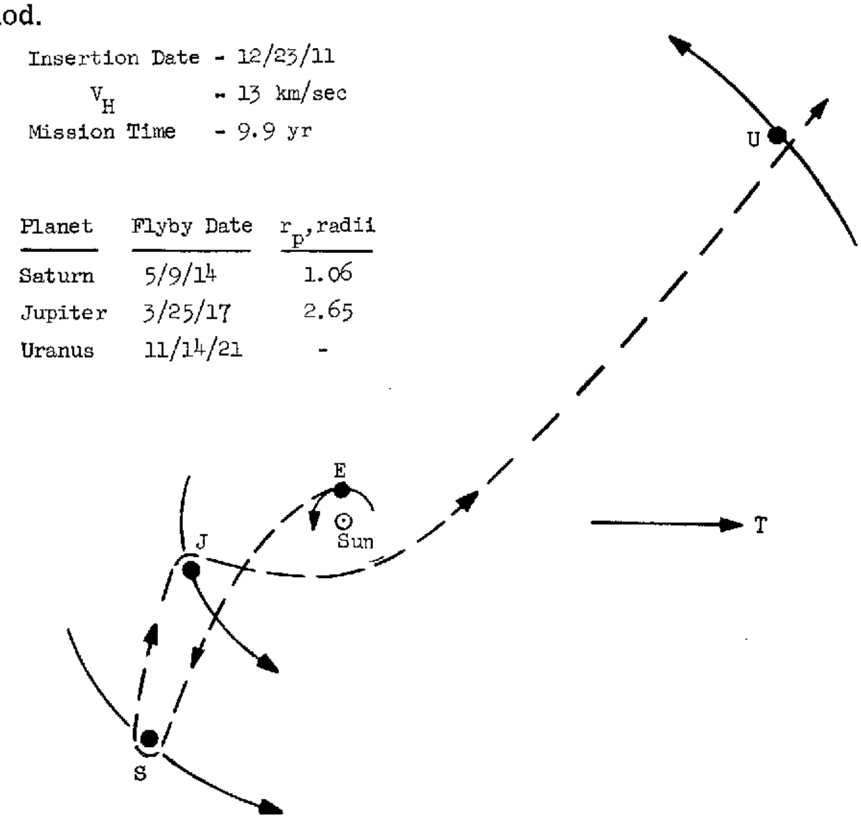


Figure 5.- Typical Saturn-first mission with direct encounter at Jupiter.

RESULTS

A few general comments are in order concerning the nature of the results to be presented. For a given launch year and flyby sequence a multitude of possible missions exist depending on insertion conditions. While a detailed and accurate analysis of any specific mission would be required to determine the effects of variations in important mission parameters, the intent of the current study was only to show general mission trends. Thus, to reduce the volume of data to be presented, the following restrictions were placed on the results to be given.

Since the Saturn-first approach was initiated by a Saturn-Jupiter sequence, only missions involving Saturn and Jupiter in combination with other outer planets are included in the report. Constraints of a practical nature were placed on launch energy and the flyby orbit at Saturn. Excess launch velocity (V_H) could not exceed 14 km/sec and the encounter at Saturn was required to either pass inside or outside the rings. Also, since a function minimization technique was used in the analysis, only minimum trip time results are presented. The minimum trip time requirement and the Saturn ring constraint reduces to no more than two the number of possible missions for a given launch year and flyby sequence. As will be shown, these two missions are positioned near the center of the available launch window for a given launch year.

Comparison of Jupiter-First and Saturn-First Missions

Two-planet missions.- Mission results for flybys of Jupiter and Saturn are summarized in table I. Shown are insertion dates, excess launch velocities, and mission times achieved using both the Jupiter-first and Saturn-first techniques. For Jupiter-first missions, the distance of closest approach at Jupiter is given, while Saturn-first results include both inner and outer ring missions.

Consider the Jupiter-Saturn (J-S) missions of table I. Two separate launch periods are shown beginning in 1976 and 1996. These result because J-S missions repeat at the mutual synodic period of about 19.9 years that exists between Jupiter and Saturn. Additional missions would of course occur at following 20-year intervals. Note that most of the J-S missions of table I utilized the maximum excess launch velocity of 14 km/sec. This resulted in the relatively low trip times shown. Lowering the maximum excess velocity available results in about a 10 to 12 percent increase in trip time for each 1 km/sec reduction in V_H (ref. 5).

Two S-J mission launch periods beginning in 1987 and again in 2006 are shown in table I. As before, these launch periods repeat at about the synodic period between Jupiter and Saturn. While the S-J missions of table I as compared with the J-S missions generally require a lower excess launch velocity, corresponding trip times for the S-J mission are seen to be significantly greater.

TABLE I.- SUMMARY OF RESULTS FOR FLYBYS OF JUPITER AND SATURN

Planet sequence	Insertion date	V_H, km/sec	Mission time, yr	Jupiter r_p, radii
E-J-S	8/76	10.7	3.3	1.0
	9/77	14.0	2.1	2.1
	10/78	14.0	1.9	4.6
	11/79	14.0	2.0	23.7
	12/80	14.0	2.3	26.4
	3/96	10.3	3.3	1.0
	4/97	14.0	2.0	1.4
	6/98	14.0	1.8	5.6
	7/99	14.0	1.9	100.0

Planet sequence	Insertion date	Inner ring Saturn pass[a]		Outer ring Saturn pass[b]	
		V_H, km/sec	Mission time, yr	V_H, km/sec	Mission time, yr
E-S-J	2/87	13.6	6.7	12.4	7.7
	2/88	13.5	6.4	12.3	7.3
	3/89	13.4	6.0	12.1	6.9
	3/90	13.3	5.7	12.0	6.5
	3/91	13.1	5.3	11.9	6.1
	4/92	12.9	5.0	11.7	5.8
	4/93	12.6	4.7	11.4	5.5
	5/94	12.1	4.6	10.9	5.6
	10/2006	14.0	6.5	12.8	7.6
	11/07	13.8	6.2	12.7	7.3
	11/08	13.7	6.0	12.5	6.9
	12/09	13.5	5.7	12.3	6.6
	12/10	13.3	5.4	12.1	6.3
	12/11	13.1	5.2	11.9	6.0
	1/13	12.8	5.0	11.5	5.8
	1/14	12.3	4.9	11.1	6.0

[a] Inner edges of rings at Saturn positioned at 1.21 planet radii (ref. 15).
[b] Outer edges of rings at Saturn positioned at 2.29 planet radii (ref. 15).

Three-planet missions.- Jupiter-first and Saturn-first mission results are summarized in tables II, III, and IV for various three-planet flybys. Shown are the insertion dates, excess launch velocities, and flyby distance at Jupiter which yield minimum trip times for missions involving both inner and outer ring passes at Saturn.

Consider table II which includes flybys of Jupiter, Saturn, and Uranus. Five launch years between 1976-1980 are shown for the J-S-U missions with the lowest trip time occurring in 1979. After 1980 this mission, along with all other three-planet Jupiter-Saturn type missions, can not be repeated for about 100 years (ref. 7).

The Saturn-first approach provides two additional launch periods (1990 to 1993 and 2009 to 2015) as shown in table II. However, a higher launch energy and total trip time is incurred using the Saturn-first procedure. For example, the lowest trip time achievable for S-J-U missions (1992) is about 3.1 years greater than the corresponding time for J-S-U missions (1979). As indicated by table II, flyby distances at Jupiter are generally lower for Saturn-first missions than for Jupiter-first missions.

TABLE II.- SUMMARY OF RESULTS FOR FLYBYS OF JUPITER, SATURN, AND URANUS

Planet sequence	Insertion date	Inner ring Saturn pass			Outer ring Saturn pass		
		V_H, km/sec	Mission time, yr	Jupiter r_p, radii	V_H, km/sec	Mission time, yr	Jupiter r_p, radii
E-J-S-U	8/76	10.2	7.5	1.0	9.2	9.1	2.1
	9/77	10.8	6.3	3.9	9.6	8.0	10.2
	10/78	11.7	5.5	9.0	10.1	7.4	23.4
	11/79	12.6	5.4	34.1	11.0	6.9	76.0
	12/80	13.4	5.6	31.2	11.8	7.4	52.3
E-S-J-U	3/90	13.3	12.0	7.0	11.5	11.7	1.0
	3/91	13.1	11.4	7.3	11.9	10.4	1.1
	4/92	12.8	8.5	1.0	11.7	12.7	1.5
	4/93	12.6	10.0	1.4			
	12/2009	13.5	10.4	2.5			
	12/10	13.3	10.1	2.5			
	12/11	13.1	9.8	2.6	11.9	11.2	4.0
	1/13	12.8	9.5	2.7	11.5	10.8	4.3
	1/14	12.3	9.3	3.0	11.1	10.8	5.6
	1/15	12.3	10.0	5.8			

TABLE III.- SUMMARY OF RESULTS FOR FLYBYS OF JUPITER, SATURN, AND PLUTO

Planet sequence	Insertion date	Inner ring Saturn pass			Outer ring Saturn pass		
		V_H, km/sec	Mission time, yr	Jupiter r_p, radii	V_H, km/sec	Mission time, yr	Jupiter r_p, radii
E-J-S-P	8/76				10.7	8.5	1.0
	9/77				13.2	6.1	1.9
	10/78				13.7	5.9	4.9
	11/79				14.0	6.7	23.7
	12/80				14.0	9.4	26.4
E-S-J-P	2/87				12.4	13.8	1.0
	2/88	13.2	11.7	1.0	12.3	15.3	1.9
	3/89	13.4	11.8	1.5			
	10/2005	14.0	13.7	1.5	12.9	15.5	2.2
	10/06	14.0	13.3	1.4	12.8	14.9	2.0
	11/07	13.8	12.8	1.3	12.7	14.1	1.5
	12/08	13.7	12.2	1.1			

Results for flybys of Jupiter, Saturn, and Pluto are summarized in table III. Jupiter-first missions of table III are achievable during the 1976 to 1980 launch period with a minimum trip time of 5.9 years occurring in 1978. These missions can only be performed using an outer ring pass at Saturn as indicated by table III. Three-planet Saturn-first flybys to Pluto were found to exist during 1987 to 1989 and again from 2005 to 2008. The S-J-P and J-S-P missions of table III are seen to be comparable with respect to launch energy requirements. However, trip times are significantly lower for Jupiter-first flybys. For example, the minimum time achieved in 1978 is about one-half of the minimum time required for the 1988 Saturn-first mission. As was the case with table II, the flyby altitudes at Jupiter are generally much lower for the Saturn-first missions.

Results are summarized in table IV for three-planet flybys of Jupiter, Saturn, and Neptune. Launch energy requirements for Saturn-first missions are seen to be consistently higher than for Jupiter-first flybys. However, the trip times for S-J-N missions compare favorably with the J-S-N results. For example, the minimum inner ring time in 2013 is only about 17 percent higher than the minimum J-S-N time in 1979. Also, the minimum outer ring time (2013) is actually lower for the S-J-N mission than for the J-S-N mission (1979).

TABLE IV. - SUMMARY OF RESULTS FOR FLYBYS OF JUPITER, SATURN, AND NEPTUNE

Planet sequence	Insertion date	Inner ring Saturn pass			Outer ring Saturn pass		
		V_H, km/sec	Mission time, yr	Jupiter r_p, radii	V_H, km/sec	Mission time, yr	Jupiter r_p, radii
E-J-S-N	8/76	9.7	11.7	1.5	9.1	13.7	1.9
	9/77	10.1	10.2	5.9	9.4	12.5	14.4
	10/78	10.8	9.3	13.5	9.9	11.9	35.3
	11/79	11.7	8.8	32.1	10.7	11.4	99.6
	12/80	12.9	9.0	40.1	11.6	12.1	55.3
E-S-J-N	3/90	13.3	14.9	7.0			
	3/91				11.9	15.9	1.4
	4/92	12.9	12.1	1.2			
	4/93	12.6	16.5	1.6			
	12/2008	13.8	12.6	1.8			
	12/09	13.5	12.0	1.7			
	12/10	13.3	11.5	1.6	12.1	12.6	2.0
	12/11	13.1	10.9	1.3	11.9	11.9	1.6
	1/13	12.8	10.3	1.0	11.5	11.3	1.1

Three-planet Jupiter-first and Saturn-first mission results given in tables II, III, and IV can be briefly summarized as follows: The Saturn-first approach opens up two additional launch windows following the 1980 cutoff date for Jupiter-first missions. The Saturn-first opportunities generally occur in the 1990 to 1994 and the 2008 to 2014 periods. Increases in launch energy requirements and mission times result for the Saturn-first technique. If the optimum launch year is considered with regards to total mission time, the Jupiter-first technique gives reductions in excess launch velocities up to about 9 percent and reductions in mission time of from about 17 to 50 percent.

Four-planet mission.- Results for a four-planet Grand Tour mission to Jupiter, Saturn, Uranus, and Neptune are summarized in table V. While after 1980 the Jupiter-first missions of table V cannot be repeated for about 179 years, the Saturn-first technique again provides new launch opportunities between 1990 to 1994. The trends with respect to insertion energy, trip time, and Jupiter flyby distance for the four-planet results of table V follow those of the previously given three-planet missions. For example, the minimum time Jupiter-first mission in 1978 requires about 9 percent less excess launch velocity and about 34 percent less time than the corresponding Saturn-first mission in 1992.

TABLE V.- SUMMARY OF RESULTS FOR FLYBYS OF JUPITER, SATURN, URANUS, AND NEPTUNE

Planet sequence	Insertion date	Inner ring Saturn pass			Outer ring Saturn pass		
		V_H, km/sec	Mission time, yr	Jupiter r_p, radii	V_H, km/sec	Mission time, yr	Jupiter r_p, radii
E-J-S-U-N	7/76	10.3	10.2	1.2			
	9/77	11.0	8.7	3.9	9.5	11.4	9.0
	10/78	11.7	8.1	9.1	10.7	10.6	22.8
	11/79	12.6	8.2	38.5	11.0	10.6	80.9
	12/80	13.3	8.6	31.2	11.9	10.8	52.5
E-S-J-U-N	3/90	13.3	16.5	7.0	11.5	16.9	1.0
	3/91	13.1	15.8	7.2			
	4/92	12.8	12.2	1.0			
	4/93	12.6	16.1	1.4			

Unique Saturn-First Missions

In addition to providing new launch opportunities following the 1980 cutoff date for Jupiter-first Grand Tour type missions, the Saturn-first approach offers other possible missions which may be unique to this technique. One such mission that involves successive flybys of Saturn, Jupiter, and Earth is illustrated in figure 6. For this mission, which can be performed during any of the launch periods shown in table I, a retrograde encounter at Jupiter is performed such that the resulting post-Jupiter transfer orbit has a near-Earth perihelion passage. This type of mission could be valuable from a data transmission standpoint since data could be stored during flybys of Saturn and Jupiter and transmitted during close approach to Earth. For example, with the mission shown in figure 6, the post-Jupiter transfer orbit is such that the vehicle remains in the sphere of influence of the Earth for about 1 day and is within 1 astronomical unit of the Earth for nearly 18 days.

Missions of the type shown in figure 6 could be adjusted such that an entry into the Earth's atmosphere could be achieved. However, the high relative velocity between the spacecraft and Earth during Earth passage (about 17.5 km/sec for the mission of fig. 6) could place severe retrieval requirements on the spacecraft.

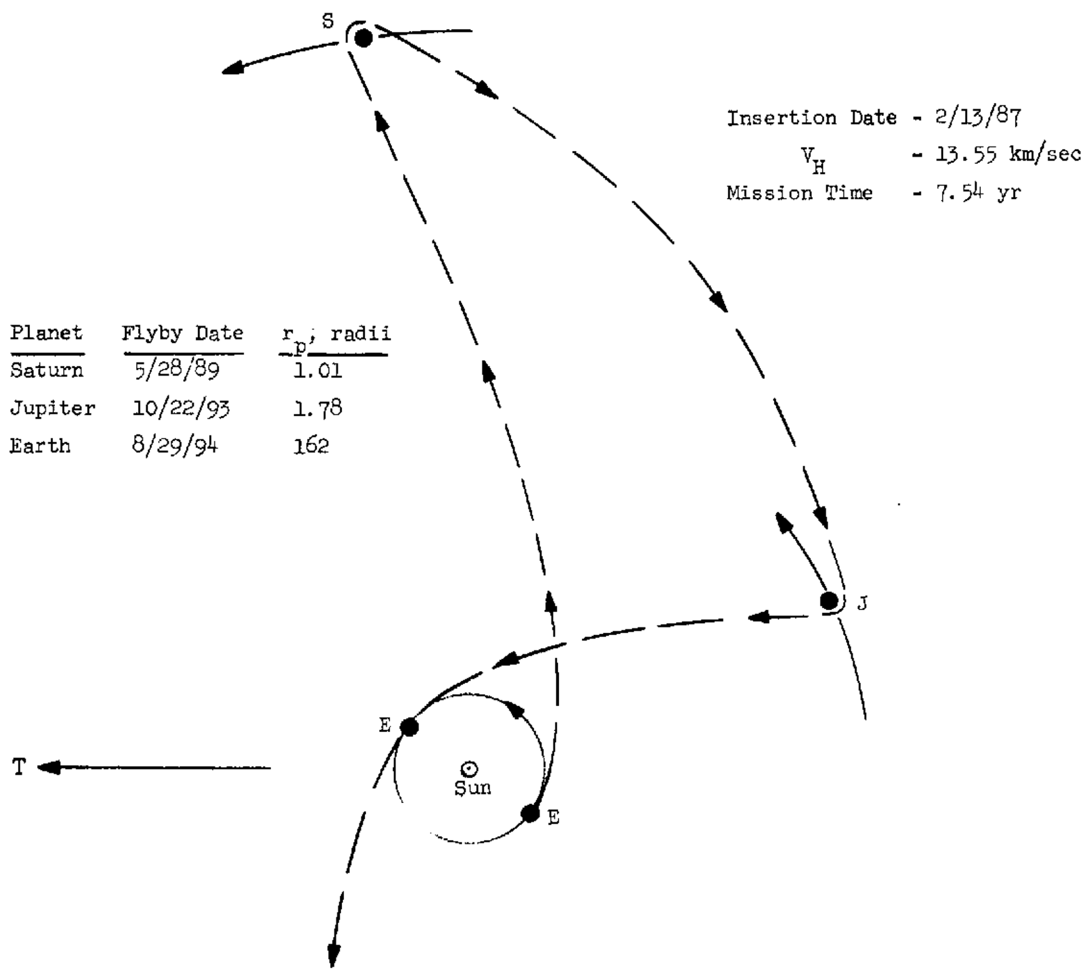


Figure 6.- Saturn-Jupiter-Earth mission.

Other options are also available for missions of the type shown in figure 6. For example, post-Jupiter orbits can be adjusted such that, following the close approach at Earth, flybys of Uranus, Neptune, or Pluto could be achieved. Also, if desired, the post-Jupiter transfer could be designed to make flybys of inner solar system planets or to perform a solar-probe mission.

Another factor which should be considered for missions of the type shown in figures 5 and 6 relates to the asteroid belt near Jupiter. The three asteroid belt passages which these missions require may either add or detract from the desirability of such missions. From a negative standpoint, these multiple passes through the belt obviously increase the probability of spacecraft impacts. However, these missions would afford three separate opportunities to investigate the asteroid belt on a single mission.

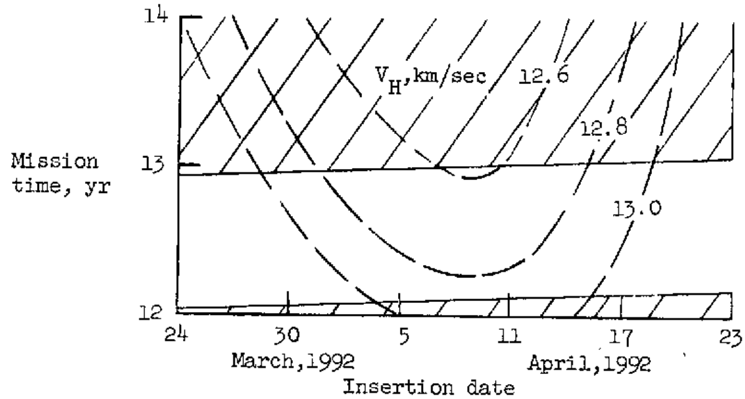
An additional mission which cannot be achieved using the Jupiter-first technique is possible with the Saturn-first approach. This mission involves flybys of all five outer planets (S-J-U-N-P). The mission can be performed during the 1991 to 1993 launch period with a minimum trip time of about 20 years resulting in 1992. While these large trip times would seem to rule out such a mission, it could be feasible if a four-planet flyby of the type shown in figure 3 was under consideration. For example, the four-planet mission of figure 3 can be extended to a five-planet mission by executing a retrograde flyby at Neptune at a flyby distance of about 1.1 planet radii. The resulting Neptune-Pluto transfer requires about 8 years which, when added to the S-J-U-N mission time of figure 3, gives a total trip time of about 20.3 years.

Launch Window Comparison for Jupiter-First and Saturn-First Missions

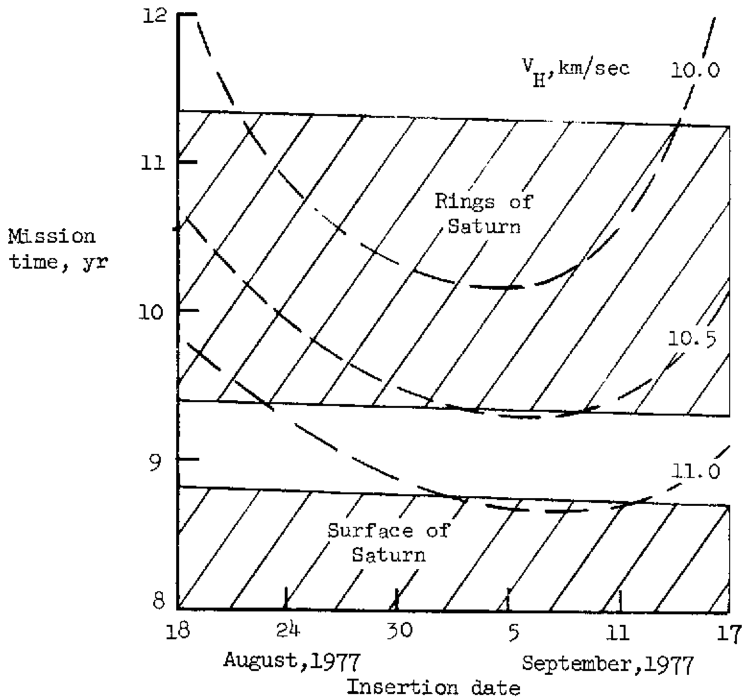
As previously outlined, the results of tables I to V are limited to those minimum trip time missions which are achievable during a given launch year. From a practical standpoint, it is of interest to examine the insertion window available for similar Jupiter-first and Saturn-first missions. While insertion window comparisons will not be made for all possible multiple outer planet flybys, results considered to be typical of Jupiter-first and Saturn-first missions are given in figure 7.

Shown in figure 7 are the insertion dates and mission times associated with various constant levels of excess launch velocity for the four-planet missions of figures 2 and 3. Superimposed are regions which would correspond to passages into the rings and under the surface of Saturn. Minimum trip times for inner and outer ring passages would generally correspond respectively to those missions which graze the surface of Saturn and the outer edge of the rings. (The surface of Saturn, as well as that of other planets, was actually taken to be at 1.01 planet radii, which should place the distance of closest approach at a point above the outer edge of the planetary atmosphere.)

The insertion windows for the Saturn-first missions of figure 7 are seen to compare favorably with Jupiter-first missions. This general trend with regards to insertion windows was found to exist for all Jupiter-first and Saturn-first missions considered.



(a) E-S-J-U-N.

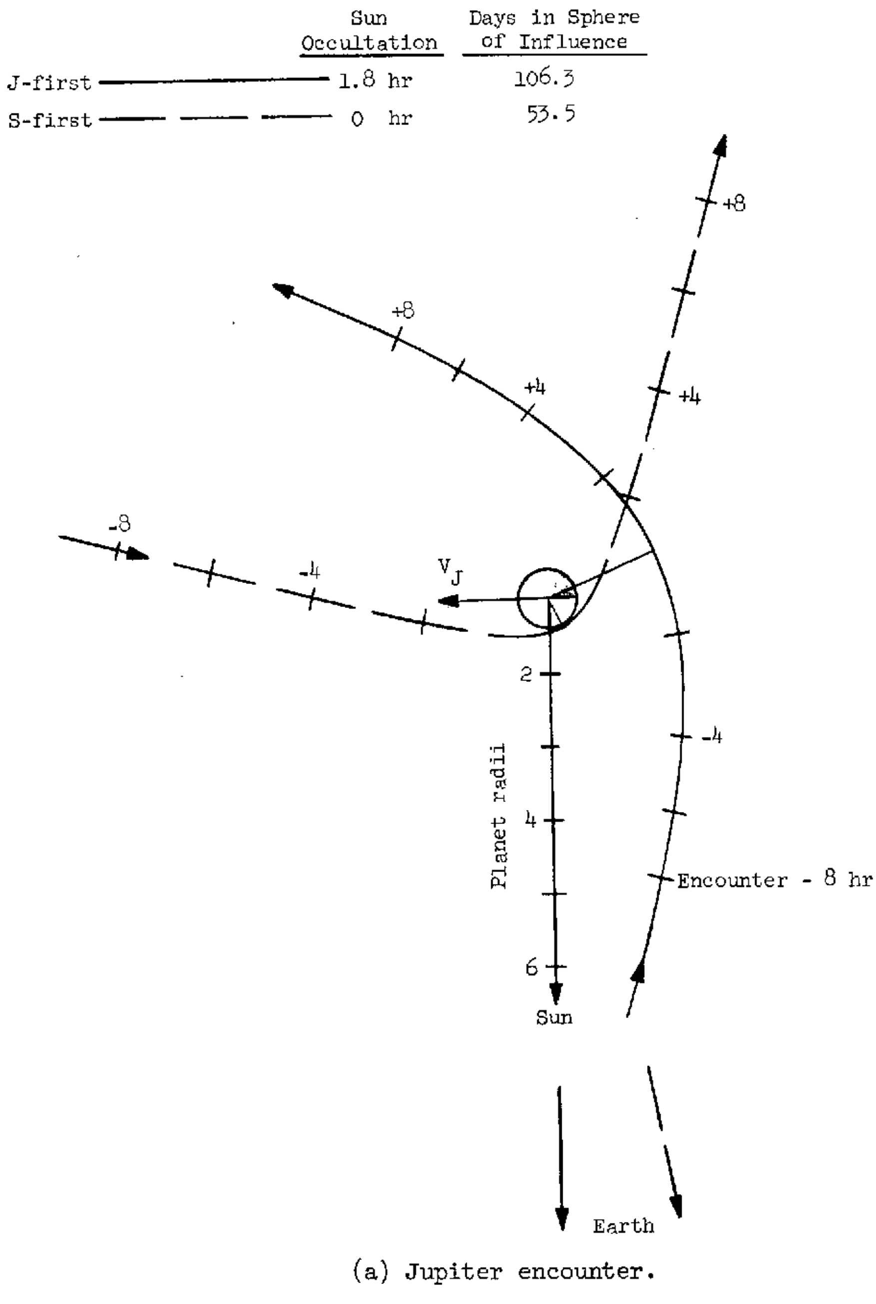


(b) E-J-S-U-N.

Figure 7.- Comparison of Jupiter-first and Saturn-first insertion windows.

Flyby Orbit Characteristics for Jupiter-First and Saturn-First Missions

It is of interest to examine the general characteristics of typical flyby orbits for missions of the type considered. Shown in figure 8 are planet referenced encounter orbits at Jupiter (fig. 8(a)), Saturn (fig. 8(b)), and Uranus (fig. 8(c)) for the Jupiter-first and Saturn-first missions of figures 2 and 3. The encounter orbits of figure 8 are to scale in terms of planet radii, and the flyby trajectory is depicted in the orbital plane of the planet.



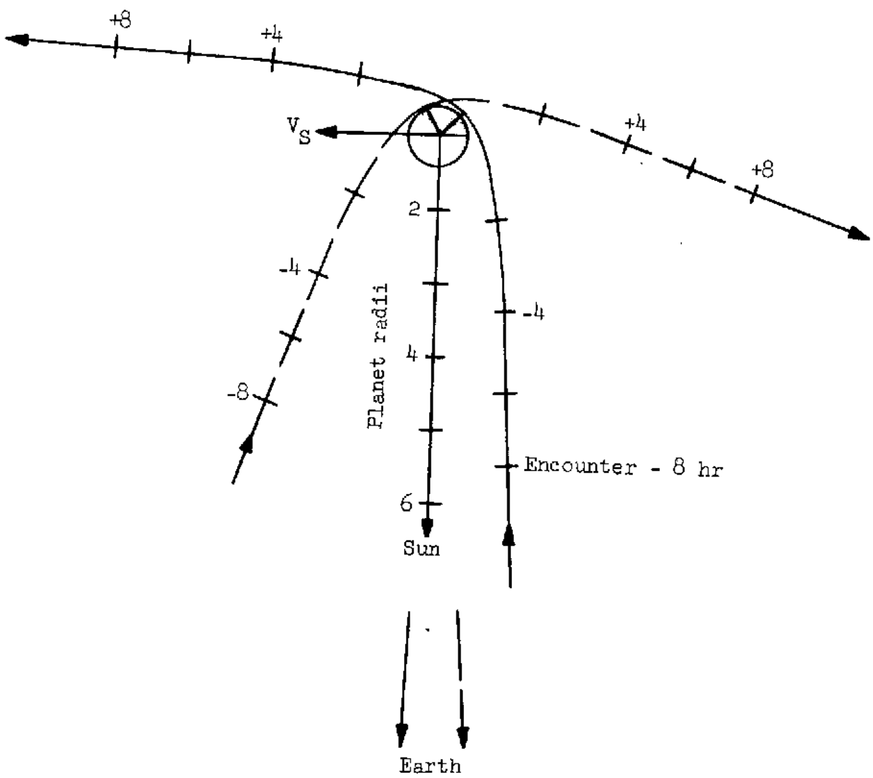
(a) Jupiter encounter.

Figure 8.- Encounter orbits for typical Jupiter-first and Saturn-first missions.

Encounter trajectories at Jupiter are given in figure 8(a). Considerable difference is seen to exist for the flyby orbits shown. Whereas the Saturn-first vehicle spends less time in the vicinity of Jupiter, the vehicle is never occulted by the planet. Also, the near pericenter portion of the orbit occurs on the sunlit side of the planet, which could enhance photographic coverage.

The Sun occultation times given in figure 8 refer to that phase of the encounter orbit during which the vehicle is on the unlit side of the planet. These Sun occultation times agree closely with the corresponding periods for which, with respect to the Earth, the vehicle is occulted by the planet. Also, with respect to the Earth, the vehicle is never occulted by the Sun during any of the encounter phases shown in figure 8.

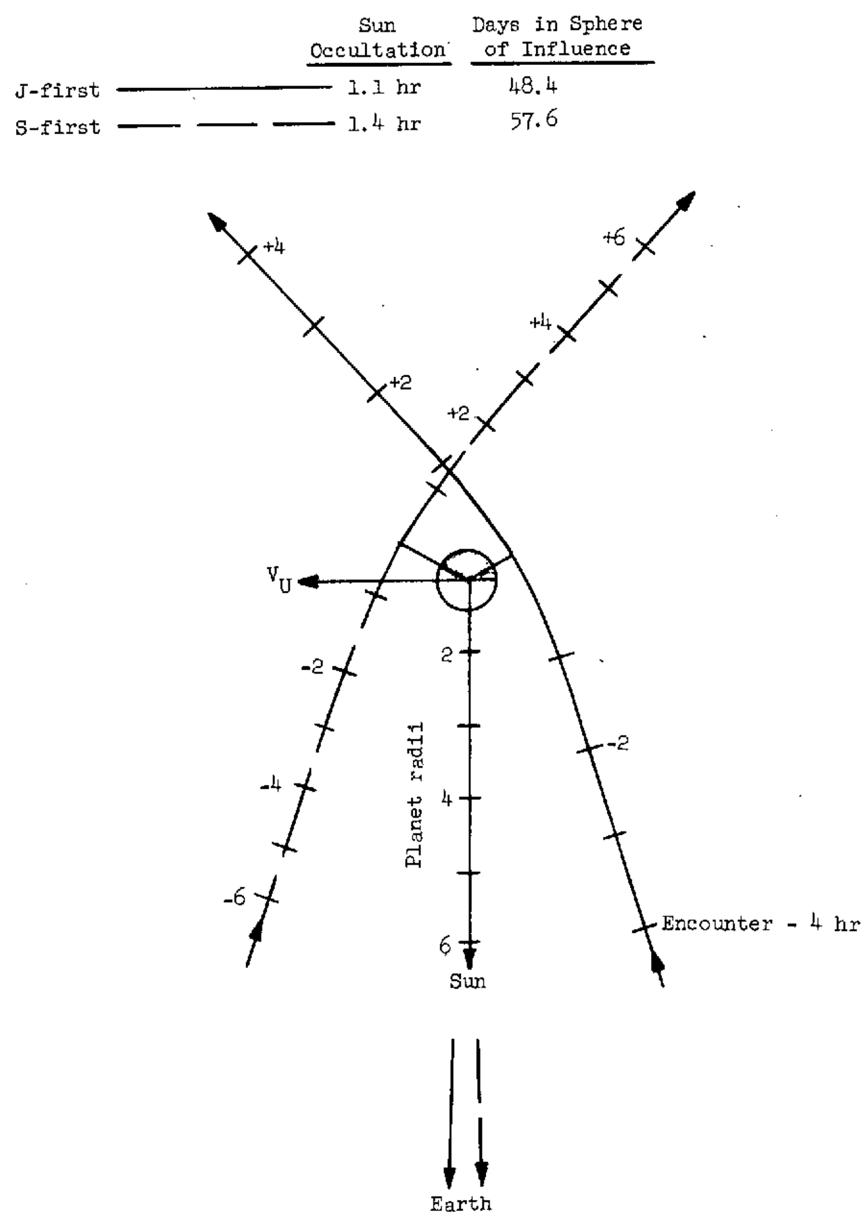
	Sun Occultation	Days in Sphere of Influence
J-first ———————	1 hr	63.8
S-first —— —— ——	.7 hr	69.7



(b) Saturn encounter.

Figure 8.- Continued.

Consider the encounter orbits at Saturn shown in figure 8(b). The Jupiter-first and Saturn-first trajectories are seen to be near mirror images of each other with the occultation times and periods spent in the planets' activity sphere corresponding closely. This same trend continues for the flyby at Uranus as revealed in figure 8(c). Again the orbits are near mirror images, with the Saturn-first encounter being somewhat faster and having a slightly longer Sun occultation time than the Jupiter-first encounter orbit.



(c) Uranus encounter.

Figure 8.- Concluded.

As previously stated, the encounter orbits of figure 8 are typical of most Jupiter-first and Saturn-first missions. Thus, the contrasting natures of Saturn-first and Jupiter-first flyby orbits provide a different range of encounter conditions. These include such scientific experiment related items as planet approach and departure conditions, areas of the planet traversed during the encounter, lighting conditions, and the Sun/Earth occultation times.

Summary of Jupiter-First and Saturn-First Mission Results

Jupiter-first and Saturn-first mission results which have been discussed in previous sections of the report are summarized in figure 9. Shown are launch opportunities for various planet sequences, as well as the range of values for trip time and excess launch velocity associated with each mission. The lower values for trip times correspond to inner ring passes at Saturn and are generally achieved with the higher launch velocities given.

Figure 9 graphically illustrates the new launch opportunities made available using the Saturn-first approach. These new opportunities seem especially attractive as a follow-on program to answer questions raised during initial flybys which may occur in the period

Planet Sequence	Insertion Date (1970, 1980, 1990, 2000, 2010, 2020)	Mission Time, yr	V_H, km/sec
J-S		1.8-3.3	10.3-14.0
S-J		4.7-7.7	10.9-14.0
J-S-U		5.4-9.1	9.2-13.4
S-J-U		8.5-12	11.1-13.5
J-S-P		5.9-9.4	10.7-14.0
S-J-P		11.7-15.5	12.3-14.0
J-S-N		8.8-13.7	9.1-12.9
S-J-N		11.5-15.9	11.5-13.8
J-S-U-N		8.1-11.4	9.5-13.3
S-J-U-N		12.2-16.9	11.5-13.3
S-J-E		5.6-8.6	10.9-14.0
S-J-U-N-P		19.9-23.5	12.6-13.1

Figure 9.- Summary of Jupiter-first and Saturn-first mission results.

before 1980. Without the Saturn-first opportunities, the formulation of any follow-on program would be difficult due to the long delays between possible missions.

The new Saturn-first opportunities shown in figure 9 do result in a significant increase in mission time and launch energy. For example, on flybys involving three or more planets, trip times associated with Saturn-first missions are on the average about 50 percent greater than those for comparable Jupiter-first missions. Corresponding increases in excess launch velocity average about 15 percent. While these increases are sizable, they may not be prohibitive considering the increased technology which should be available in the next decade.

While it may be of only academic interest, an additional point concerning three-planet Saturn-first missions should be noted. The time interval between the two launch windows beginning in about 1990 and again around 2008 is approximately the same as the Jupiter-Saturn synodic period (19.9 yr). While only two launch windows are shown in figure 9, these missions can actually be performed during other launch years with the repeat cycle again being about 20 years. This was confirmed by calculating a limited number of three-planet missions occurring in the early 1970's as well as in the late 2020's. Thus, while three-planet Jupiter-first missions of the type considered in this report are repeatable only about every 100 years (ref. 7), Saturn-first missions can apparently be repeated at approximate integer multiples of the 19.9-year synodic period between Jupiter and Saturn. In addition, four-planet (S-J-U-N) missions were also found possible around 2010 but the resulting trip times were from 20 to 30 years.

SUMMARY OF RESULTS

Results have been presented from a study of procedures for providing more frequent launch opportunities for multiple-planet Grand Tour type missions to the outer solar system. A Saturn-Jupiter flyby sequence was used in the analysis to initiate the mission instead of the normal Jupiter-Saturn sequence. The Saturn-first approach was shown to yield additional launch opportunities following the 1980 cutoff date for Jupiter-first missions. The results of this study can be summarized as follows:

1. Launch opportunities in the 1990 to 1994 and 2008 to 2014 periods were shown to exist for three-planet (Saturn-Jupiter-Uranus, Saturn-Jupiter-Pluto, and Saturn-Jupiter-Neptune) flyby missions.

2. Launch opportunities in the 1990 to 1994 period were shown to exist for a four-planet (Saturn-Jupiter-Uranus-Neptune) mission.

3. A unique five-planet mission to Saturn-Jupiter-Uranus-Neptune-Pluto occurs in the early 1990's.

4. Certain Saturn-first missions appear attractive from a data-transmission standpoint since the post-Jupiter transfer orbit can be adjusted to pass as close to Earth as desired.

5. Saturn-first missions offer a new range of encounter conditions as compared with Jupiter-first missions. These include approach and departure conditions, regions of the planet traversed during encounter, and time intervals during which the vehicle is occulted by the planet with respect to the Earth and Sun.

6. Available launch windows for Jupiter-first and Saturn-first missions were found to be comparable.

7. Multiple passes through the asteroid belt at Jupiter on some Saturn-first missions could be of value in studying the belt.

8. For flybys involving the same planets, Saturn-first as compared with Jupiter-first missions required increases in launch energy requirements and total trip times. For minimum trip time trajectories, Saturn-first missions generally required about 15 percent greater excess launch velocities and from about 17 to 100 percent longer trip times than comparable Jupiter-first missions.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., September 12, 1973.

APPENDIX

SYMBOLS

E,J,S / U,N,P	Earth, Jupiter, Saturn, Uranus, Neptune, and Pluto, respectively
i_A, i_D	heliocentric inclinations of vehicle pre-encounter and post-encounter trajectories, respectively
i_I	heliocentric inclination of vehicle insertion trajectory at Earth
i_p	inclination of flyby trajectory with respect to equatorial plane of encounter planet
r_A, r_D	approach and departure distances of vehicle from Sun at encounter
r_I	distance from vehicle to Sun at insertion
r_P	distance from planet to Sun at encounter
r_p	distance of closest approach of vehicle to encounter planet
V_A, V_D	heliocentric approach and departure velocities of vehicle during encounter
V_a, V_d	asymptotic approach and departure velocities of vehicle during encounter
V_H	hyperbolic excess launch velocity of vehicle at insertion
V_I	heliocentric velocity of vehicle at insertion
V_P	heliocentric velocity of planet
γ_A, γ_D	heliocentric approach and departure flight-path angles of vehicle
γ_I	heliocentric flight-path angle of vehicle at insertion
δ	gravity-turn or deflection angle during encounter
Υ	vernal equinox

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