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SUMMARY

Exploration of the four major moons of Jupiter could provide valuable scientific information on the process by which these moons and our solar system were formed. This report presents a systematic study of round-trip trajectories to the four major moons of Jupiter; Io, Europa, Ganymede, and Callisto.

The general mission considered has a total trip time of 1000 days with a 100-day stay at Jupiter. The mission begins with a 1.1 circular orbit at Earth and uses atmospheric braking at Earth return. Flybys of the moons of Jupiter and stopovers there are considered.

Nonstop lunar flybys made by modifying a Jupiter nonstop flyby yielded the lowest propulsive velocity increments (6.0 to 7.39 mi/sec; 9.65 to 11.9 km/sec) but the highest lunar passage velocities (10 to 20 mi/sec; 16 to 32 km/sec). Lunar flybys made from a 25-day Jupiter parking orbit required about twice the propulsion (16.8 mi/sec; 27 km/sec) but gave lower passage velocities (3.5 to 5 mi/sec; 5.6 to 8 km/sec). For the lunar stopover mission, the lowest total propulsive velocity increment $\sum \Delta V$ (15.6 mi/sec; 25 km/sec) occurred for the following conditions:

(1) The moons were visited starting from the outermost and proceeding to the innermost.

(2) The arrival at the first moon and the departure from the last moon were by maneuvers that involved three propulsive impulses.

(3) Elliptic parking orbits were used at the moons.

The stopover mission can also be accomplished from a Jupiter parking orbit but with a slightly higher propulsive requirement.

The possibility is discussed herein of using multiphase interplanetary trajectories and refueling techniques for the interlunar maneuvers to reduce the propulsion requirements for some of the systems.

INTRODUCTION

A recent study of nonstop and orbital stopover round trips to Jupiter (ref. 1) has shown that propulsive velocity increments and trip durations comparable to those being considered for Mars round trips can be obtained. This encouraging result led to the present study of the mission modes and the propulsion requirements for nonstop and orbital stopover round trips to the four major moons of Jupiter. Round trips are of interest for manned missions and as a method of data retrieval for unmanned probes.

As discussed in reference 2, the Jupiter lunar exploration mission presents an opportunity to acquire valuable scientific data pertaining to the process by which our solar system was formed. The Jovian lunar system is remarkably similar in form to our solar system because it has both an inner system of dense moons and a vast outer system of less dense moons. There are 12 moons in all, but the four major moons are of the greatest scientific interest.

Density estimates indicate that the moons Io and Europa (Jupiter I and II) are probably metallic or rocky in nature, while Ganymede and Callisto (Jupiter III and IV) probably have rocky cores with outer layers of solidified water and carbon dioxide. Some astronomers believe that this indicates that Io and Europa were formed from a molten state and that Ganymede and Callisto were formed by cold aggregation. They also believe that Jupiter rather than the Sun was the heat source during the formation of Io and Europa. An exploration of the four major moons could possibly provide valuable information on the processes by which the moons of Jupiter and our solar system were formed.

There are few existing studies of round-trip trajectories to the moons of Jupiter. Reference 3 presents one-way trajectories to Jupiter. Reference 4 is a summary report on missions to all the major bodies in our solar system including round-trip missions to Ganymede, the most massive of the Jovian moons. In the latter study, the primary emphasis was on the variation in the initial weight in Earth orbit required to perform the mission, as a function of the type of propulsion system used. The study included unmanned flybys and manned and unmanned orbital missions, as well as manned landings on Ganymede. However, only direct trajectories ending in a low circular lunar orbit or on the lunar surface were considered. The present study does not estimate system weight but does consider a much wider variety of possible lunar exploration trajectories and visits to more than one moon.

The present study includes primarily round-trip flybys of and orbital stopovers at the four major moons of Jupiter; Io, Europa, Ganymede, and Callisto. Some consideration is given to trips to fewer than four of the major moons. Trajectories to the moons include direct arrival from and departure to interplanetary space by single-, double-, and triple-impulse maneuvers; and from a parking orbit about Jupiter. The best sequence for visiting the moons is determined, and the effect of elliptic parking orbits and atmospheric braking at the moons is shown. Some of the missions considered use refueling tankers during the interlunar phase of the mission, and some require multiple manned or observational vehicles. Although the study is limited to round-trip flyby and orbital missions, some of the results can apply to nonreturn and lunar landing missions.

METHOD OF ANALYSIS

Assumptions and Approximations

Reference 1 is a study of the propulsive velocity increments for nonstop and orbital stopover trips to Jupiter using elliptic parking orbits. Results from that study for favorable Jupiter parking orbits are summarized in figure 1. The data points indicate discrete

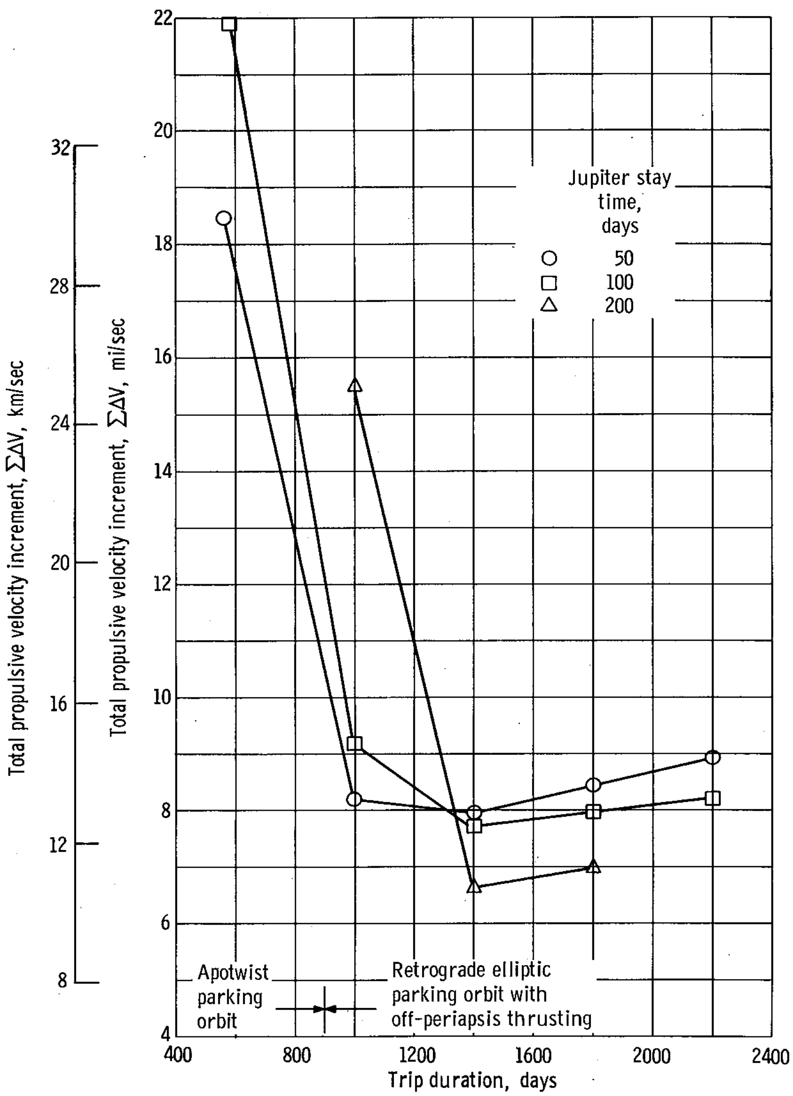


Figure 1. - Propulsion requirements for representative Jupiter stopover round trips. Atmospheric braking at Earth return.

local minimums. (These data are based on elliptic parking orbits and account for the problems in attaining the required orientation of the Jupiter arrival and departure trajectories.) For Jupiter stay times of 50 and 100 days, these data show only a modest change in $\sum \Delta V$ with decreasing trip time down to 1000 days. (All symbols are defined in the appendix.) From 1000 to 600 days, there is an abrupt increase in $\sum \Delta V$. Based on this observation, a 1000-day trip time was used for the present study.

The data also show that at a 1000-day trip time, there is only a modest increase in $\sum \Delta V$ when the stay time is increased from 50 to 100 days. However, there is a sharp rise in $\sum \Delta V$ for stay times between 100 and 200 days. Also, as is shown later, the 100-day stay time is compatible with the lunar explorations considered herein. The present study uses only 100 days stay for the stopover missions. While the 1000-day trip with 100 days stay is selected for purposes of illustration, many of the concepts discussed herein are applicable to other mission and stay times.

The interplanetary outbound and return trajectories are symmetrical; that is, the outbound and inbound heliocentric travel angles ψ_o and ψ_b are equal, and the outbound and inbound travel times are equal (figs. 2(a) and 3(a)).

The four major moons of Jupiter are the destinations in the present study. They are assumed to be in circular coplanar orbits, which also lie in the plane of the Earth-Jupiter transfers. Table I presents the physical and orbital data for Jupiter and the four moons, as given in reference 2. These data indicate that the assumptions made are reasonable approximations for a preliminary study.

The periapsides of Jupiter flybys and parking orbits, the periapsides of the lunar parking orbits, and the radii of the lunar circular parking orbits are 1.1 times the body radius. For Jupiter, it is assumed that this value yields a periapsis above the sensible atmosphere.

The interlunar (from one moon to the next) transfers are assumed to be made by coasting ellipses or semiellipses, which are tangent to the lunar orbits at the apsides of the ellipses. Propulsive velocity increments are applied only at the apsides of the transfer ellipses. These transfers are of the Hohmann type which give a minimum propulsive velocity increment. The associated transfer times appear acceptable. Propulsive velocity increments ΔV are assumed to be impulsive. In the case of lunar flyby trajectories, the perturbation of the vehicle trajectory caused by the passage of the vehicle through the lunar sphere of influence is neglected. In practice this perturbation can be made small by selecting a sufficiently high lunar passage altitude.

While primary attention is given to using propulsive braking at the moons, the possible advantages of atmospheric braking are illustrated. Atmospheric braking is assumed to be possible for entry from an interlunar transfer but not for direct arrival from the interplanetary transfer, for which the approach velocities are much greater. At present it is not certain that the Jovian moons possess an atmosphere (ref. 5).

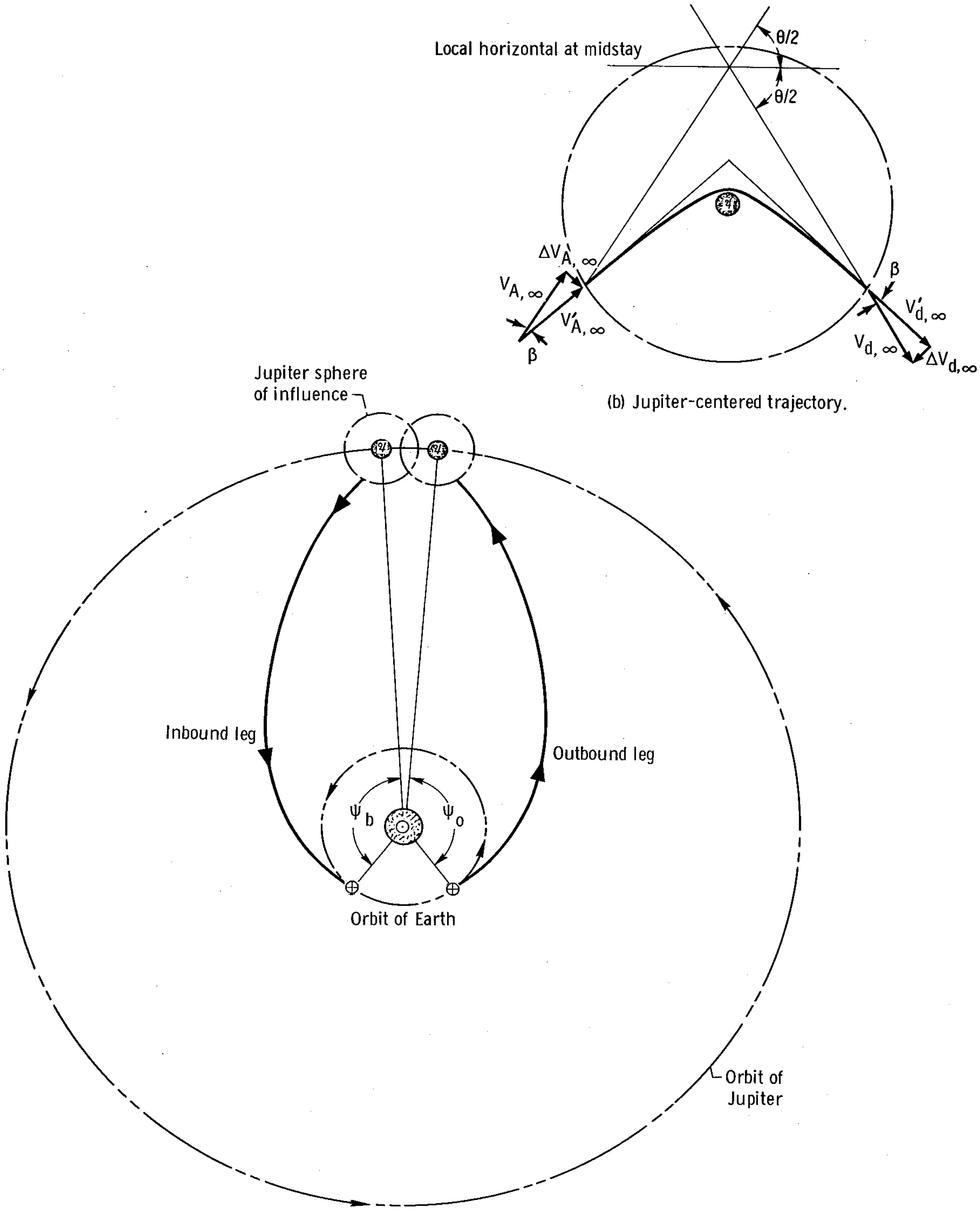
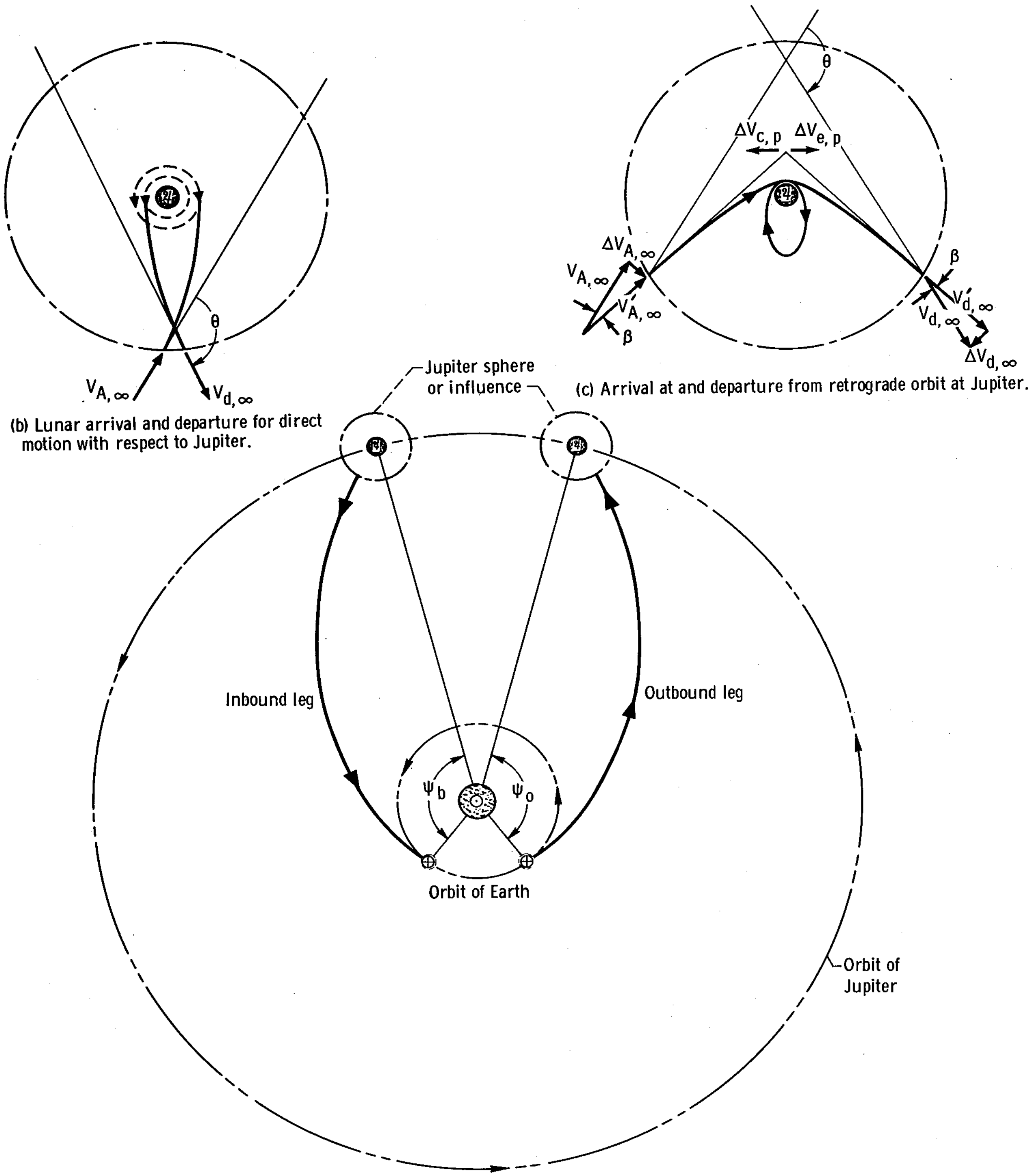


Figure 2. - Typical Jupiter nonstop round trip. Zero stay time.



(b) Lunar arrival and departure for direct motion with respect to Jupiter.

(c) Arrival at and departure from retrograde orbit at Jupiter.

(a) Interplanetary trajectory.

Figure 3. - Typical Jupiter stopover round trip.

TABLE I. - PHYSICAL AND ORBITAL DATA FOR JUPITER AND ITS MOONS (REF. 2)

[Direction of orbital motion, direct.]

Celestial body	Orbital radius		Mean inclination of lunar orbit to orbit of Jupiter, deg	Eccentricity of orbit, e	Orbital period, days	Orbital velocity		Sphere of influence radius	
	mi	km				mi/sec	km/sec	mi	km
Jupiter	4.825×10^{8}	7.765×10^{8}	-----	0.0484	4328.9	8.1	13.0	2.99×10^{7}	4.81×10^{7}
Io (I)	2.65×10^{5}	4.21×10^{5}	3.138	0	1.769	10.75	17.3	4.5×10^{3}	7.24×10^{3}
Europa (II)	4.17×10^{5}	6.71×10^{5}	3.565	.0003	3.552	8.53	13.7	5.78×10^{3}	9.3×10^{3}
Ganymede (III)	6.65×10^{5}	10.7×10^{5}	3.222	.0015	7.155	6.75	10.86	1.54×10^{4}	2.48×10^{4}
Callisto (IV)	1.17×10^{6}	1.88×10^{6}	3.965	.0075	16.689	5.08	8.17	2.24×10^{4}	3.6×10^{4}

Celestial body	Body radius		Gravitational parameter, μ		Circular velocity at 1.1 radii		Parabolic velocity at 1.1 radii	
	mi	km	mi^3/sec^2	km^3/sec^2	mi/sec	km/sec	mi/sec	km/sec
Jupiter	4.34×10^{4}	6.98×10^{4}	3.03×10^{7}	12.7×10^{7}	25.2	40.5	35.6	57.3
Io (I)	1.158×10^{3}	1.86×10^{3}	1.16×10^{3}	4.85×10^{3}	.953	1.53	1.35	2.17
Europa (II)	9.78×10^{2}	15.7×10^{2}	7.5×10^{2}	31.4×10^{2}	.836	1.34	1.18	1.89
Ganymede (III)	1.6×10^{3}	2.57×10^{3}	2.475×10^{3}	10.35×10^{3}	1.185	1.91	1.68	2.7
Callisto (IV)	1.608×10^{3}	2.58×10^{3}	1.548×10^{3}	6.47×10^{3}	.934	1.5	1.32	2.12

For those trips that utilize an intermediate parking orbit about Jupiter, the direction of motion in the parking orbit must be direct, that is, in the direction of motion of the moons. If the lunar exploration vehicle orbits Jupiter in a retrograde motion the approach to the moons is in the retrograde direction, and the passage velocities at the moons will be so high as to make flyby missions of questionable value. These lunar orbital missions would also require a very high $\sum \Delta V$.

Description of Typical Trajectory

All trips (figs. 2(a) and 3(a)) begin with the vehicle in a circular orbit about the Earth at a distance of 1.1 Earth radii. A propulsive velocity increment is impulsively applied to send the vehicle towards Jupiter on the outbound interplanetary transfer path.

On arrival at Jupiter's sphere of influence the velocity relative to Jupiter is $V_{A,\infty}$, and the direction is defined by the path angle with respect to the local horizontal at midstay $\theta/2$. Within the sphere of influence there are three possible courses of action depending on the type of interlunar mission:

(1) For a nonstop flyby (fig. 2(b)), a propulsive velocity increment is applied at Jupiter's sphere of influence to obtain the required propulsive turning angle β that, together with the gravity turning, will yield the total required turning angle θ.

(2) For a stopover mission with direct arrival at one of the moons (fig. 3(b)), the vehicle enters Jupiter's sphere of influence and falls through its gravitational field to the radius of the moon's orbit about Jupiter, where a propulsive velocity increment is applied to place the vehicle in the desired lunar capture orbit.

(3) For lunar flyby and orbital missions originating in a Jupiter parking orbit (fig. 3(c)), the vehicle also falls through Jupiter's gravitational field until it reaches approximately 1.1 Jupiter radii. At this point a propulsive velocity increment is applied to place the vehicle in an elliptic parking orbit about Jupiter with a periapsis of 1.1 Jupiter radii and with the desired orbital period.

For direct arrival at a moon, the direction of rotation of the space vehicle about Jupiter is in the direct direction (i.e., the direction of the moons). For entry into a parking orbit, the direction of rotation is retrograde because this yields the lower interplanetary ΔV.

The interlunar exploration phase can be carried out by using several possible trajectories. For nonstop flyby missions, a perturbation of the optimum nonstop Jupiter flyby is used. For lunar flyby missions from a Jupiter parking orbit, the flyby can be accomplished by ellipse transfers originating at either apse of the parking orbit or by sequential semiellipse transfers beginning at one apse of the parking orbit and terminating at the other apse. Lunar stopover missions both with and without a Jupiter parking orbit are accomplished by sequential semiellipse transfers between the moons and with circular and elliptic lunar capture orbits. A more detailed description of each mission is given in the section RESULTS AND DISCUSSION.

Since only symmetrical interplanetary trips are considered, departure from Jupiter's sphere of influence is essentially the reverse of the arrival maneuver. The vehicle is returned to the surface of the Earth by atmospheric braking at the end of the inbound interplanetary transfer trajectory.

The equations and methods of calculation necessary to solve for numerical values of the propulsive velocity increments and for the times required to perform the maneuvers involved in all the trajectories to be discussed are given in reference 1 or depend only on elementary orbital relations that may be found in reference 2, for example.

RESULTS AND DISCUSSION

In this section the results of the trajectory analyses are presented: first, for Jupiter lunar flyby missions with and without a Jupiter parking orbit and, then, for Jupiter lunar orbiting stopover missions with and without a Jupiter parking orbit.

Lunar Flybys Without Jupiter Parking Orbit

This trajectory is a perturbation of the optimum Jupiter flyby illustrated in figure 2(b). The vehicle falls through Jupiter's gravitational field and passes Jupiter once at a minimum distance of 1.1 Jupiter radii. The amount by which the optimum flyby must be modified to allow for flybys of the four major moons depends primarily on the positions of the moons when the vehicle arrives at Jupiter's sphere of influence. The flybys are illustrated schematically in figure 4.

Favorable lunar positions. - If the moons are in a favorable position, a single vehicle moving along the optimum Jupiter flyby trajectory will fly by all four major moons, at no additional cost. In this case, the vehicle on its way to a 1.1-Jupiter-radii periapsis passes each moon as it crosses that moon's orbit. The passage is at nearly right angles

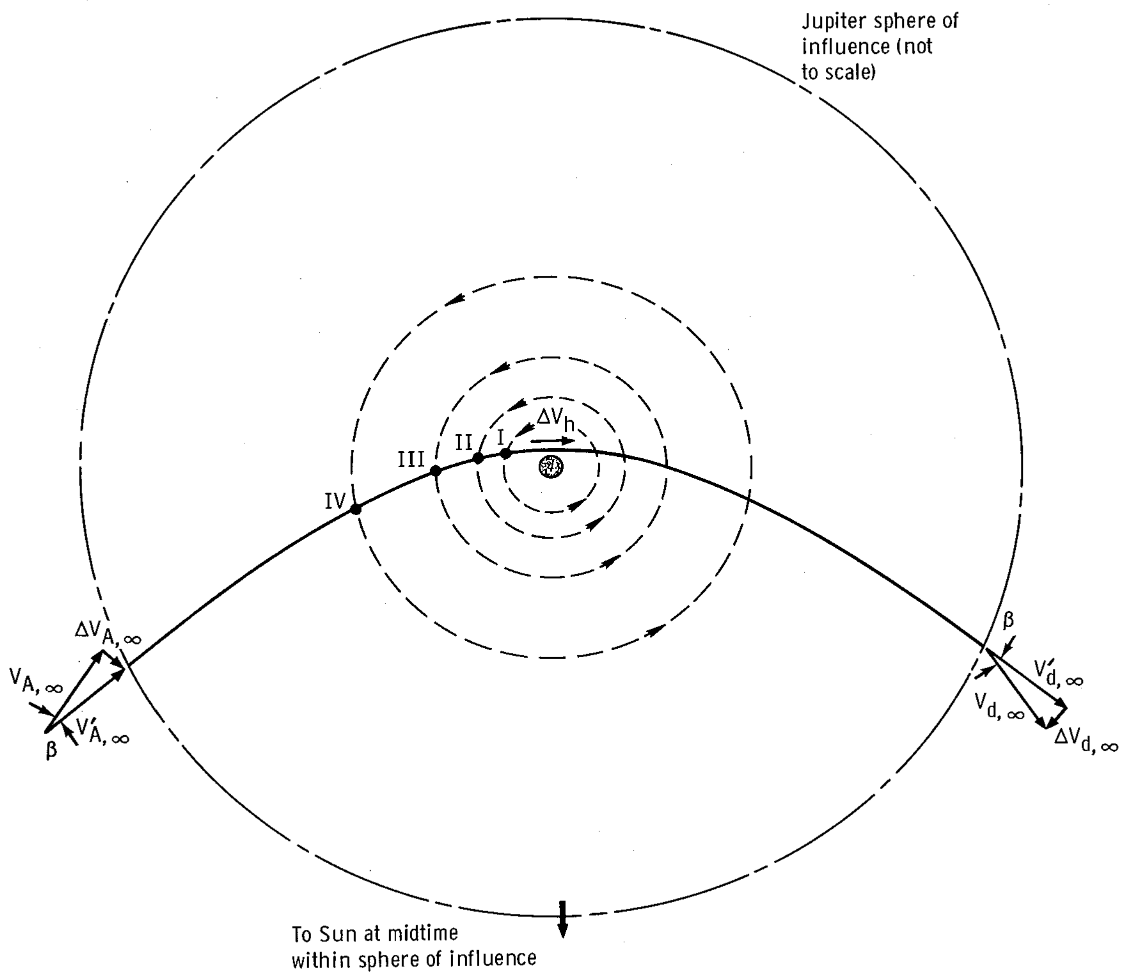


Figure 4. - Jupiter-lunar nonstop flyby. Jupiter periapsis, 1.1 Jupiter radii.

to the orbits, and the passage velocities range from 10 to 20 miles per second (16 to 32 km/sec).

Unfavorable lunar positions. - The problem considered herein is how to perform a four-moon lunar flyby when the moons are not conveniently located in their orbits. It will always be possible to intercept one moon by adjusting the Earth departure date, even for a fixed outbound-leg time. This adjustment will cause only a small change in the ΔV required to depart from Earth, as may be judged by the data of reference 1. Thus, it is assumed that the Earth departure date is selected so that the main interplanetary vehicle intercepts Callisto (Moon IV), the outer moon and the one with the longest orbital period. The problem of unfavorable lunar positions now applies only to the three inner moons. Three secondary vehicles are assumed, one to go to each of the three inner moons. If the main vehicle on an unmodified trajectory inbound to Jupiter would just miss Moon III, the following maneuver would be used by the secondary vehicle. At the Jupiter sphere of influence a propulsive velocity increment (e.g., $\Delta V_{A,\infty}$ in fig. 4) which has a retrograde component would be applied to increase the passage time from the sphere of influence to the moon by approximately one lunar orbital period so that the secondary vehicle will intercept the moon on its leg inbound to Jupiter. This propulsive velocity increment is also oriented to yield half the propulsive turning angle required at Jupiter.

A second posigrade propulsive velocity increment ΔV_h is applied to the secondary vehicle as it passes the trajectory periapsis at 1.1 Jupiter radii. This velocity increment decreases the time of passage from the periapsis to the sphere of influence by approximately one lunar orbital period to allow the secondary vehicles and the main vehicle to arrive at the sphere of influence simultaneously.

A third propulsive velocity increment $\Delta V_{d,\infty}$ is applied at the sphere of influence leaving Jupiter to obtain the other half of the required propulsive turning angle and the correct departure velocity for the inbound transfer to Earth. If this type of maneuver is applied to the secondary vehicle going to each of the inner moons, the velocities of the three secondary vehicles and the main spacecraft will be equal, and their physical locations will be nearly the same, so that rendezvous can be accomplished.

The example just discussed assumed that a flyby was achieved on the inbound leg and by initially slowing down. If a flyby on either the inbound or outbound leg is considered, then a delay of approximately one half of a lunar period in the transfer time from the sphere of influence to the moon is required for the worst lunar position. If, in addition, a flyby using an acceleration at the arriving sphere of influence is considered, then approximately a quarter of a lunar period increase or decrease in the passage time from the sphere of influence to the moon will accommodate the worst lunar position. The magnitude of the ΔV required to fly by any moon is directly related to the period of the lunar orbit. The requirement for a long delay means that the vehicle must be slowed down more, which requires a larger ΔV. By this argument, to fly by the outermost moon, Callisto, which has the longest period (16.7 days), would require the largest ΔV. For this reason, the Earth departure date was selected so that the main spacecraft flew by Callisto.

The individual velocity increments for flybys of the moons and for several delays in the transfer time from the sphere of influence to the moon are given in table II. Total mission propulsive velocity increments are given in the first row of table III. The values of $\sum \Delta V$ vary from 6.0 miles per second (9.65 km/sec) for the unmodified Jupiter flyby vehicle, which also passes Callisto, to an estimated 7.39 miles per second (11.9 km/sec) for a flyby of Ganymede, the moon which can require the greatest $\sum \Delta V$. (This value was estimated for a change of one-quarter lunar period (plus or minus) in the transfer time from the sphere of influence to the moon.)

The propulsive velocity increments for the lunar flyby also depend on the distance from Jupiter at which the initial and final maneuvers are made. The sphere of influence was a convenient choice. Larger distances would yield lower velocity increments.

TABLE II. - INDIVIDUAL PROPULSIVE VELOCITY INCREMENTS REQUIRED NEAR JUPITER FOR JUPITER-LUNAR NONSTOP FLYBYS

[Trajectory periapsis, 1.1 Jupiter radii.]

Moon	Delay, fraction of lunar orbital period	Required propulsive velocity increment, ΔV						Sum of propulsive velocity increments near Jupiter, $\sum \Delta V_{\infty} + \Delta V_h$	
		Arrival at Jupiter sphere of influence, $\Delta V_{A,\infty}$		Trajectory periapsis, 1.1 Jupiter radii, ΔV_h		Departure from Jupiter sphere of influence, $\Delta V_{d,\infty}$			
		mi/sec	km/sec	mi/sec	km/sec	mi/sec	km/sec	mi/sec	km/sec
Callisto (IV)	0	0.6	0.96	----	-----	0.6	0.96	1.2	1.93
	0.5	.6	.96	----	-----	.6	.96	1.2	1.93
	1.0	.6	.96	----	-----	.6	.96	1.2	1.93
Ganymede (III)	0	0.6	0.96	----	-----	0.6	0.96	1.2	1.93
	0.5	1.0	1.61	0.4	0.643	1.19	1.91	2.59	4.17
	1.0	1.64	2.64	.87	1.4	2.37	3.81	4.88	7.85
Europa (II)	0	0.6	0.96	----	-----	0.6	0.96	1.2	1.93
	0.5	.802	1.29	0.15	0.24	.91	1.46	1.86	3.0
	1.0	.954	1.53	.35	.56	1.13	1.82	2.43	3.91
Io (I)	0	0.6	0.96	----	-----	0.6	0.96	1.2	1.93
	0.5	.7	1.12	0.08	0.13	.71	1.14	1.49	2.39
	1.0	.735	1.18	.17	.27	.8	1.28	1.7	2.73

TABLE III. - SUMMARY OF RESULTS FOR FOUR-MOON LUNAR FLYBY MISSIONS

[Mission time, 1000 days.]

Mission	Moons visited	Propulsive velocity increment, ΔV														Lunar passage velocity		Stay time at Jupiter, days	Figure
		Interplanetary phase						Parking orbit direction of motion reversals, $2\,\Delta V_{r,a}$		Transfer and interlunar phases $\sum \Delta V_i$ $\sum \Delta V_{t1}$ $\sum \Delta V_{t2}$		Near Jupiter for flyby, $\sum \Delta V_\infty + \Delta V_h$		Mission total, $\sum \Delta V$					
		Earth departure $\Delta V_{d,\oplus}$		Jupiter capture $\Delta V_{c,op}$		Jupiter escape $\Delta V_{e,op}$													
		mi/sec	km/sec	mi/sec	km/sec	mi/sec	km/sec	mi/sec	km/sec	mi/sec	km/sec	mi/sec	km/sec	mi/sec	km/sec	mi/sec	km/sec		
Jupiter lunar flyby without a Jupiter parking orbit[a] (modified Jupiter flyby)	Io (I) Europa (II) Ganymede (III) Callisto (IV)	4.8 ↓	7.72 ↓	---- ↓	---- ↓	---- ↓	---- ↓	---- ↓	---- ↓	----- ↓	----- ↓	1.49 1.86 2.59 1.2	2.39 3.0 4.17 1.93	6.29 6.66 7.39 6.0	10.12 10.71 11.9 9.65	10 to 20 ↓	16 to 32 ↓	0 ↓	4 ↓
Flyby from periapsis[b] of 25-day parking orbit	All four major moons	5.2	8.37	2.07	3.33	2.07	3.33	2.28	3.67	5.2	8.37	----	----	16.82	27.07	3.5 to 5	5.6 to 8	[c]99.46	6(a)
Flyby from apoapsis of 10-day parking orbit[b]	All four major moons	5.2	8.37	2.2	3.54	2.2	3.54	4.18	6.73	6.32	10.17	----	----	20.1	32.34	0 to 3.7	0 to 5.9	[d]135.7	6(b)
P-IV-III-II-I-A flyby from 25-day parking orbit[b]	All four major moons	5.2	8.37	2.07	3.33	2.07	3.33	2.28	3.67	11.37	18.2	----	----	22.99	36.99	1.5 to 3.7	2.4 to 5.9	[d]98.62	6(c)

[a]One-half lunar period delay from sphere of influence to moon.

[b]Periapsis of parking orbit at 1.1 Jupiter radii.

[c]Minimum time plus one orbital period of Callisto and Europa and two orbital periods of Ganymede and Io plus time for parking orbit conversion.

[d]Time required if moons are in worst possible position for lunar flyby. Earth escape ΔV and Jupiter capture escape ΔV correspond to mission with 100-day stay.

Lunar Flybys From Jupiter Parking Orbit

For this mission profile, the complete space vehicle enters a parking orbit about Jupiter. The vehicle system includes the Jupiter-departure and Earth-return systems, as well as the lunar exploration system. The first two items remain in the parking orbit. The lunar flybys are then made by the lunar exploration system using elliptic orbits about Jupiter that are tangent to the lunar orbits. At the end of the lunar flybys, the exploration vehicle must rendezvous with the items left in the parking orbit, in order to make the return to Earth.

Choice of Jupiter parking orbit. - The maneuver used to acquire the elliptic parking orbit about Jupiter is shown in figure 5. The direction of the approach hyperbolic velocity $V_{A,\infty}$ is determined by the interplanetary trajectory. The orientation of the parking ellipse is determined by the assumption of a symmetrical trajectory, that is, the major axis of the ellipse is the Jupiter-Sun line at midstay at Jupiter. The angle η defining the

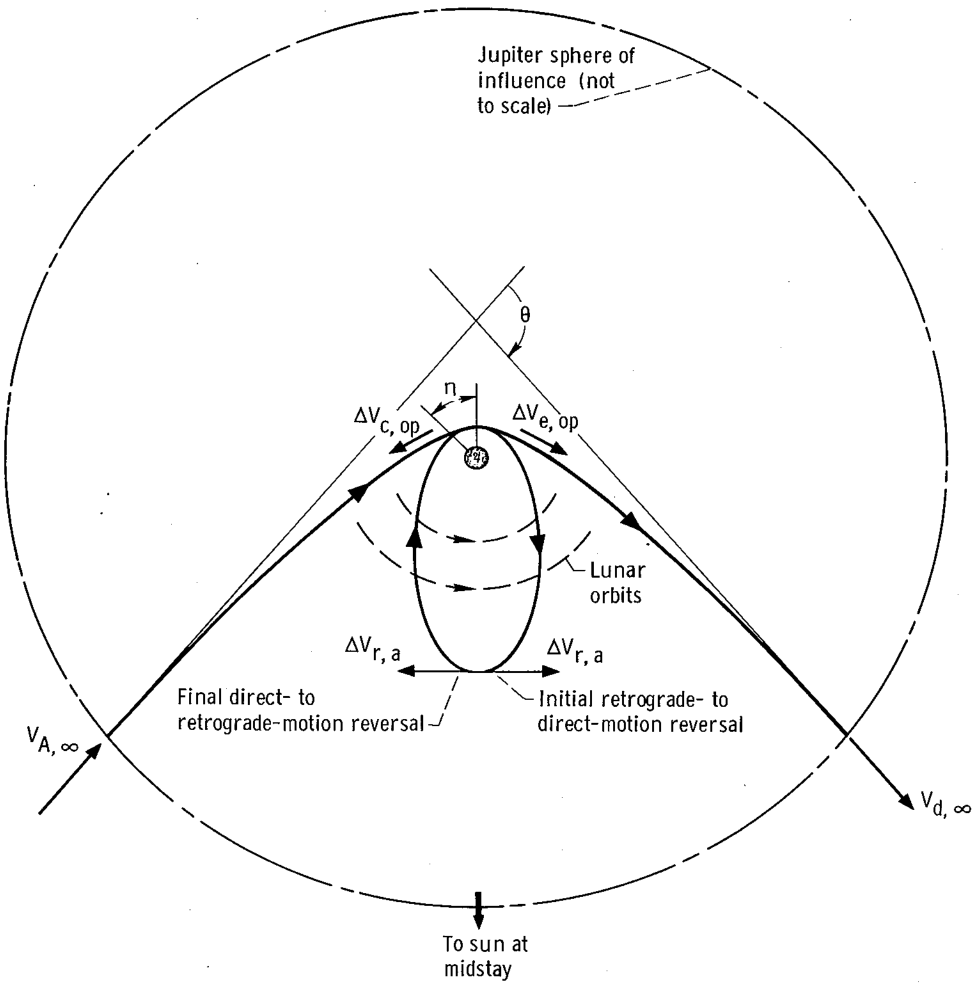


Figure 5. - Maneuvers for arriving and departing Jupiter parking ellipse using off-periapsis thrusting from retrograde ellipse. Retrograde-direct reversals at parking ellipse apoapsis; periapsis, 1.1 Jupiter radii.

intersection of the arrival trajectory and the parking ellipse is then selected to minimize the arrival ΔV. This analysis can be made by assuming entry into either a retrograde-motion parking orbit (fig. 5) or a direct-motion parking orbit, in which case the ellipse periapsis would be on the Sun side of Jupiter. In reference 1, it was found that, because of the trajectory angles associated with a 1000-day trip with 100 days stay, the retrograde-motion parking orbit gave lower interplanetary propulsive velocity increments to arrive at and depart from a parking ellipse. The velocity increment for the arrival maneuver into an ellipse with a 100-day period was 1.90 miles per second (3.05 km/sec) for retrograde motion compared with 2.58 miles per second (4.15 km/sec) for direct motion, a difference of 0.68 mile per second (1.1 km/sec).

It was previously decided that the motion in the Jupiter parking orbit should be direct to minimize the passage velocities between the moons and the flyby vehicles. There is another way to acquire a direct parking orbit, as illustrated in figure 5. The space vehicle first enters a retrograde-motion elliptical parking orbit. When the vehicle reaches the apoapsis of the orbit, a ΔV equal to twice the apoapsis velocity is applied in the retrograde direction. This procedure converts the parking orbit to one that is geometrically similar but with direct motion. The ΔV for reversing a 100-day-period ellipse from retrograde to direct motion is 0.44 mile per second (0.708 km/sec).

For the 1000-day trip with 100 days stay, a small advantage in ΔV results from arrival into a retrograde-motion orbit with reversal to direct motion at the apoapsis. Also, in the first method, the whole space vehicle enters the direct motion orbit and is subject to the higher ΔV. In the second method, the space vehicle enters the retrograde orbit with its lower ΔV, and only the lunar exploration system must undergo the reversal ΔV. The subsequent discussion is based on this latter case.

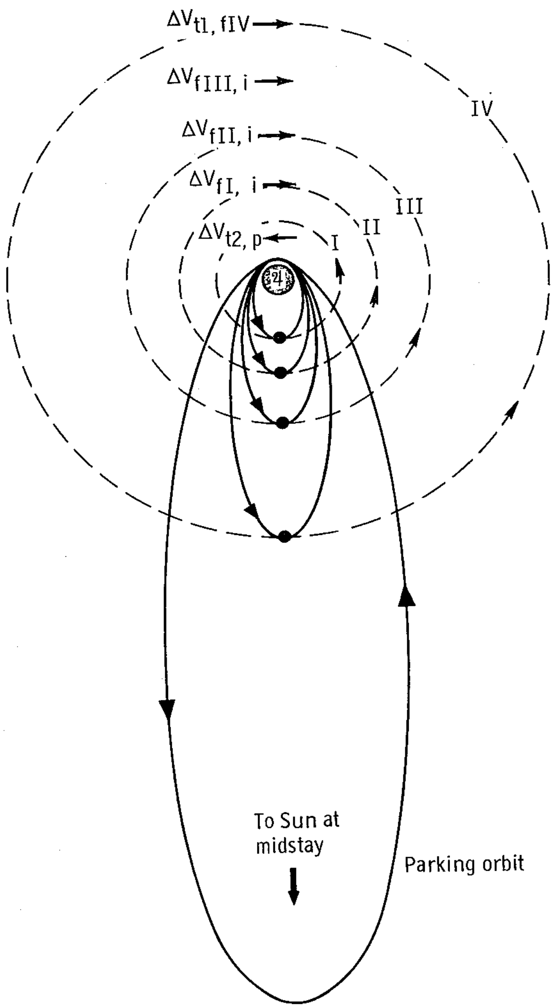
In reference 6, two ways to achieve a low ΔV while acquiring an elliptic parking orbit are mentioned. As applied to the present problem, the first method is to place the periapsis of the parking orbit as close to Jupiter as possible. In this study, a periapsis distance of 1.1 Jupiter radii was chosen as the lowest permissible altitude to avoid the sensible atmosphere. The second way is to increase the parking orbit period, by increasing its apoapsis, to the largest possible time consistent with the constraint of 100 days stay time. The longer period decreases both the propulsive velocity increment required to enter the retrograde Jupiter parking orbit and the velocity increment required to reverse the orbit to direct motion. Another constraint on the Jupiter parking orbit is discussed in the next section.

All the preceding remarks on the choice of a Jupiter parking orbit are equally true for lunar stopover missions from a Jupiter parking orbit, and therefore will not be repeated when the lunar orbiting stopover missions are discussed. Having decided how to establish the parking orbit, consideration is given to conducting the lunar flybys (1) by ellipses from the parking orbit periapsis, (2) by ellipses from the parking orbit apoapsis, and (3) by sequential semiellipse transfers.

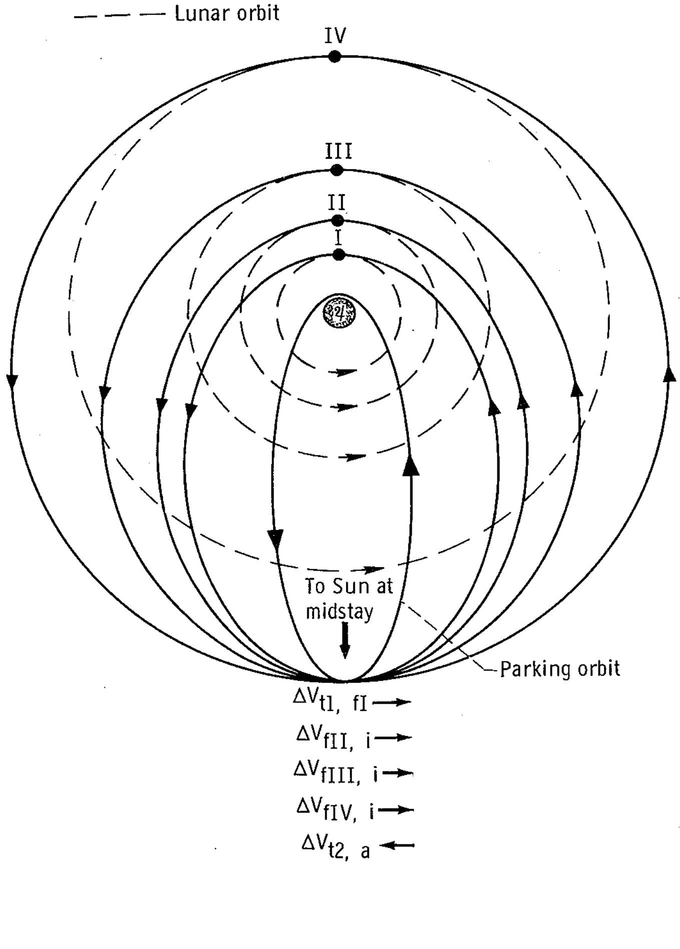
Flybys from parking orbit periapsis. - In this type of flyby (fig. 6(a)), propulsive velocity increments are applied each time the lunar vehicle arrives at the parking orbit periapsis. The velocity increments are retrograde, and their magnitude is such that the apoapsis of the vehicle orbit is just tangent to the orbit of each of the moons in turn. After completing the flybys a direct motion propulsive velocity increment is applied to return to the initial parking orbit.

For the most favorable lunar positions, the moons will always arrive at the point of vehicle orbit apoapsis at the same time as the vehicle so that the trajectory will be exactly as shown in figure 6(a) and will require a total transfer time of 11.4 days.

In the case of the most unfavorable lunar positions, a full lunar orbital period of the



(a) Flyby from periapsis of 25-day-period direct-motion parking ellipse.



(b) Flyby from apoapsis of 10-day-period direct-motion parking ellipse.

Figure 6. - Four-moon lunar flyby from Jupiter parking orbit.

destination moon must be made between ending the previous lunar flyby transfer and beginning the transfer to the moon in question. This procedure is accomplished by sending the lunar vehicle into an intermediate waiting ellipse between successive flyby ellipses. The period of the waiting orbit is the orbital period of the destination moon divided by some integer N chosen so that the apoapsis of the waiting orbit falls between the orbit of the moon just visited and the orbit of the next moon to be visited. In this case, the propulsive velocity increment required to perform the flybys is the same as that for the most favorable lunar position case, but the total transfer time to fly by all four moons can be as high as 40.5 days, instead of 11.4 days. The 40.5-day time assumes that the first moon to be visited is also in an unfavorable position and causes a waiting period.

If the conservative view is taken that the time required to complete all the flybys will be 40 days, the maximum allowable Jupiter parking orbit period is 30 days, since the retrograde - direct motion reversal requires two parking orbit periods to complete, and the total stay time is limited to a maximum of 100 days. However, because both the arrival at and the departure from the Jupiter parking orbit occur near the parking ellipse periapsis, another constraint on the parking orbit choice is that its period be the stay time at Jupiter divided by an integer (i.e., 100/N). This constraint exists because the interplanetary spaceship was left in a parking orbit and the lunar spaceship must rendezvous with it. The parking orbit period that satisfies this constraint and is less than the allowable 30 days mentioned previously is 25 days.

The propulsive velocity increments to perform the complete flyby mission, including the interplanetary phase, from the periapsis of a 25-day parking orbit are also given in table III (p. 12). The total propulsive velocity increment is approximately twice that required for the flyby of any one moon without a Jupiter parking orbit.

The flyby from the parking orbit periapsis can be done with only a single lunar vehicle in addition to the systems left in the parking orbit. However, multiple-vehicle flybys involving two, three, or four secondary lunar vehicles are also possible. One vehicle should always fly by Callisto only, since this flyby requires the greatest amount of time to accomplish. The remaining secondary lunar vehicles fly by one or more of the other moons and enter waiting orbits along the way so that all the lunar vehicles arrive at the parking orbit periapsis as the Callisto vehicle arrives from its flyby. Rendezvous is then accomplished by adjusting the velocities to that of the main vehicle. In this manner, the interlunar transfer time is decreased and the parking orbit period can be correspondingly increased, which results in a slight reduction (about 1 percent) in propulsive velocity increment for the interplanetary trajectory.

Flybys from parking orbit apoapsis. - In a similar manner, flybys can be accomplished by applying a direct-motion velocity increment each time the lunar vehicle arrives at the parking orbit apoapsis. This procedure increases the periapsis of the flyby ellipse until it is tangent to the orbit of the next moon to be visited, as illustrated in figure 6(b). A final retrograde velocity increment is applied to return to the initial parking orbit.

The most favorable lunar positions result in a total transfer time of 69.3 days. This time is the sum of the periods of the four elliptical orbits which are tangent to both the parking apoapsis and the lunar orbits. It also includes one parking orbit period because time is counted from the periapsis of the parking orbit. In this example, the parking orbit period was selected as 10 days.

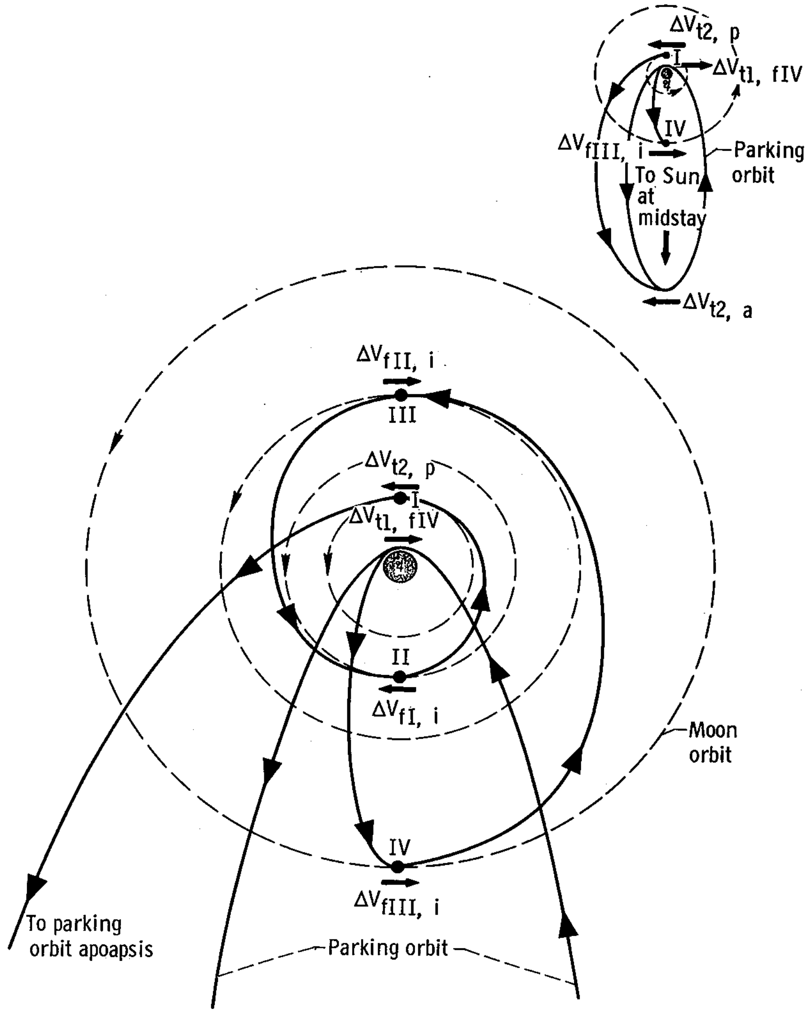
For unfavorable lunar positions, the interlunar exploration vehicle enters a waiting orbit like that defined for flybys from the parking orbit periapsis. The time to complete the flybys is the time previously given for the favorable lunar positions plus the time spent in the waiting orbits, a total of 135.7 days. This time exceeds the allowed 100-day stay time, even for the 10-day-period parking orbit assumed. This time would be still larger if a longer period parking ellipse had been picked.

The characteristics of this mission are also listed in table III. Because of the shorter parking orbit period, the propulsive velocity increments required to enter the parking orbit and for the retrograde to direct-motion reversal are larger than for the flybys from the parking orbit periapsis, where the parking orbit period was 25 days. Thus, the flybys from the parking orbit apoapsis are inferior to the flybys from the parking orbit periapsis in terms of both the propulsive velocity increment and the time required to perform the mission. However, they have lower lunar passage velocities.

Flybys by sequential semiellipse transfers. - The previous two flyby methods involved flyby trajectories which were complete ellipses with velocity increments applied every 360°. A third possible flyby trajectory involves using semiellipse transfers with velocity increments applied every 180° of revolution about Jupiter, as illustrated in figure 6(c).

In table III, an example is given using a P-IV-III-II-I-A visitation sequence (see appendix) originating in a 25-day Jupiter parking orbit. The designation P-IV-III-II-I-A represents a trip in which the vehicle transfers from the parking orbit periapsis to Callisto, visits the moons in the order Callisto, Ganymede, Europa, and Io, and returns to the parking orbit apoapsis from Io.

Assuming unfavorable lunar positions results in a stay time almost equal to that for the flybys from the parking orbit periapsis. The propulsive velocity increment required is appreciably larger than that for the flybys from the parking orbit periapsis primarily because of the larger velocity increment required by the sequential semiellipse method in the interlunar phase. This condition was true for all the lunar visitation sequences analyzed.



(c) Sequential flyby, P-IV-III-II-I-A, from 25-day-period direct-motion parking ellipse.

Figure 6. - Concluded.

Summary of Results for Lunar Flybys

The results for lunar flyby missions are summarized in table III. First, compare the trips using a parking orbit. The flybys from the parking orbit periapsis give the lowest $\sum \Delta V$ (16.82 mi/sec; 27.07 km/sec) and lunar passage velocities of 3.5 to 5.0 miles per second (5.6 to 8.0 km/sec). Flybys from the parking orbit apoapsis and the sequential lunar flyby each yield higher $\sum \Delta V$ (about 20 mi/sec; 32 km/sec) and passage velocities less than 3.7 miles per second (5.9 km/sec). For these flybys from a parking orbit, the lunar passage is parallel to the lunar orbital path, and this accounts for the low passage velocities. These missions can be accomplished by a single lunar excursion vehicle, although multiple excursion vehicles could also be used.

For the Jupiter lunar flyby without a parking orbit the total velocity increments are about half those for the cases with a parking orbit. However, the lunar passage velocities are 10 to 20 miles per second (16 to 32 km/sec), much higher than those for the flybys from a parking orbit. Also, three secondary vehicles are required for a four-moon flyby. A complete mission analysis is required to evaluate the significance of the $\sum \Delta V$ and passage-velocity differences for the different mission modes.

The preceding discussion considered Jupiter lunar flyby missions. The following discussion considers Jupiter lunar orbiting stopover missions, where the stopover is a lunar parking orbit.

Interlunar Phase of Lunar Orbiting Stopover Missions

Interlunar transfer sequence. - For lunar orbital missions the interlunar phase is defined to begin in a parking orbit about the first moon and to end in a parking orbit about the last moon. If the capture orbit required for the lunar vehicle at each moon is specified, the velocity increment and the time required to transfer between any two moons may be calculated uniquely for the semiellipse transfers assumed in this study.

The information can be displayed conveniently in tabular form. Table IV lists the velocity increment and the transfer time as functions of the arrival and departure moon, as well as of the type of lunar capture orbit. For example, the data at the intersection of the row Europa and the column Io are for the transfer from Europa to Io. The following values are given:

(1) The total ΔV required to leave Europa and to arrive at Io if a 1.1-lunar-radii parking orbit at each moon is assumed

(2) The total ΔV required to leave Europa and to arrive at Io with a parabolic "parking" orbit at each moon. The term "parabolic parking" is used in this report to refer to the limiting case, eccentricity equal to 1, of an elliptic parking orbit.

(3) The ΔV required to leave Europa from a low circular parking orbit with atmospheric braking (no propulsive velocity increment) at Io

(4) The transfer times for favorable lunar positions

(5) The transfer times for unfavorable lunar positions

Primary attention is given in this discussion to propulsive maneuvers. An examination of these sets of numbers shows that the interlunar sequence that yields the lowest $\sum \Delta V$ is IV-III-II-I or I-II-III-IV. The former of these two possibilities is selected for a reason discussed in the next section.

For the favorable position, the destination moon is in the proper configuration for a transfer at the desired launch date. The time listed is the semiellipse transfer time. For the unfavorable position, it is assumed that the favorable launch opportunity was just missed and that it is necessary to wait a synodic period. The second time listed is the

TABLE IV. - INTERLUNAR TRANSFER POSSIBILITIES FOR LUNAR ORBITING STOPOVER MISSIONS

Depart from -	Arrive at -												Definition
	Io (I)			Europa (II)			Ganymede (III)			Callisto (IV)			
	mi/sec	km/sec	days	mi/sec	km/sec	days	mi/sec	km/sec	days	mi/sec	km/sec	days	
Io (I)				1.57	2.53	----	2.75	4.42	-----	3.82	6.15	-----	(a)
				.836	1.34	----	1.86	3.0	-----	3.04	4.89	-----	(b)
				.825	1.32	----	1.55	2.49	-----	2.34	3.76	-----	(c)
				-----	-----	1.31	-----	-----	2.09	-----	----	4.0	(d)
				-----	-----	4.83	-----	-----	4.44	-----	----	5.98	(e)
Europa (II)	1.57	2.53	----				1.33	2.14	-----	2.32	3.75	-----	(a)
	.836	1.34	----				.496	.798	-----	1.59	2.56	-----	(b)
	.75	1.2	----				.647	1.04	-----	1.33	2.14	-----	(c)
	-----	----	1.3				-----	-----	2.62	-----	----	4.66	(d)
	-----	----	4.83				-----	-----	9.67	-----	----	9.17	(e)
Ganymede (III)	2.76	4.42	----	1.33	2.14	----				1.28	2.06	-----	(a)
	1.86	3.0	----	.496	.798	----				.404	.65	-----	(b)
	1.195	1.92	----	.69	1.11	----				.694	1.12	-----	(c)
	-----	----	2.09	-----	-----	2.62				-----	----	5.74	(d)
	-----	----	4.44	-----	-----	9.67				-----	----	18.28	(e)
Callisto (IV)	3.82	6.15	----	2.32	3.73	----	1.28	2.06	-----				(a)
	3.04	4.89	----	1.59	2.56	----	.404	.65	-----				(b)
	1.45	2.33	----	.99	1.59	----	.59	.949	-----				(c)
	-----	----	4.0	-----	-----	4.66	-----	-----	5.74				(d)
	-----	----	5.98	-----	-----	9.17	-----	-----	18.28				(e)

[a]Propulsive velocity increments (ΔV_i) required to leave one moon and to arrive at next moon with 1.1-lunar-radii parking orbit at each moon.

[b]Propulsive velocity increments (ΔV_i) required to leave one moon and to arrive at next moon with parabolic "parking" orbit at each moon.

[c]Propulsive velocity increment required to leave 1.1-lunar-radii parking orbit with atmospheric braking at destination moon.

[d]Transfer time between each pair of moons.

[e]Transfer time between each pair of moons plus one synodic period.

sum of the transfer time and the synodic period between the two moons.

Choice of lunar stay times and parking orbits. - There are two simple methods to achieve a specified stay time at a moon. The first is to allow multiple revolutions in a circular orbit of 1.1 lunar radii. This method has the advantage that it yields long periods of close observation of the lunar surface. Also, the orbital period of the parking orbit about the moon is small compared with the orbital period of the moon about Jupiter or with the interlunar transfer time. Hence, the departure from the circular parking orbit can be made with cotangential thrusting from the position that gives the proper interlunar flight direction for transfer to the next moon. This procedure gives the lowest possible ΔV for the given parking orbit. In short, the orientation problem that exists for an elliptic parking orbit does not occur for a circular parking orbit. A disadvantage of the low circular orbit is that a comparatively large ΔV is required to enter and leave this orbit.

If a minimum propulsive velocity increment is more important than a long observation time, the specified stay time can be achieved by entering an elliptic capture orbit with a period equal to the stay time at the moon. A loosely captured elliptic orbit requires lower velocity increments than a low circular orbit, but the time spent near the moon (i. e., when the vehicle is in the vicinity of the orbit periapsis) is only a small fraction of the total lunar stay time.

The actual decrease in the velocity increment required for lunar capture as a function of the period of the elliptic orbit is shown in figure 7. Using elliptic lunar parking orbits presents the problem of orienting the ellipse so that the arrival and departure maneuvers can be made from the periapsis. This problem occurs in interplanetary round trips, when elliptic parking orbits are used at the destination planet (refs. 1 and 6). It is assumed herein that the required orientation is achieved by using the apotwist maneuver of reference 6.

The ΔV savings that result from using elliptic lunar parking orbits with the maximum apotwist maneuver of 180° is given by the solid curve in figure 7. The short-dashed curve is the ΔV savings with no ellipse orientation penalty. The real case should be between these two limits. The long-dashed curve in figure 7 is the asymptotic value corresponding to an infinite period ellipse (a parabolic orbit).

In general, in planning a lunar exploration mission, the total stay time to be spent at the four moons will be specified. A pertinent question then is how to distribute this stay time among the various moons. Figure 7 shows that the greatest reduction in the overall propulsive velocity increment is obtained by distributing the stay time approximately equally among the four moons. Only an approximately equal stay-time distribution is possible as a result of timing problems related to waiting for the correct lunar configuration to begin the next transfer.

A timing problem is also associated with reentering the Jupiter parking orbit or the inbound Earth-return transfer. This problem is easily solved by adjusting the stay time at the last moon visited. At most, the vehicle could be 360° away from the proper position for departing the moon, which means that the greatest correction in the lunar stay time would be equal to one lunar orbital period. For this reason, the IV-III-II-I transfer sequence was chosen rather than the I-II-III-IV sequence, which by symmetry has the same required velocity increment. For the IV-III-II-I sequence, the maximum time adjustment is 1.77 days, the orbital period of Io, whereas the I-II-III-IV sequence might require a 16.69-day time adjustment. This adjustment represents a larger fraction of the total allowable Jupiter stay time of 100 days and therefore is less desirable.

Performance in interlunar phase. - This phase begins and ends in a lunar parking orbit. The performance characteristics for a IV-III-II-I order of lunar visitation are

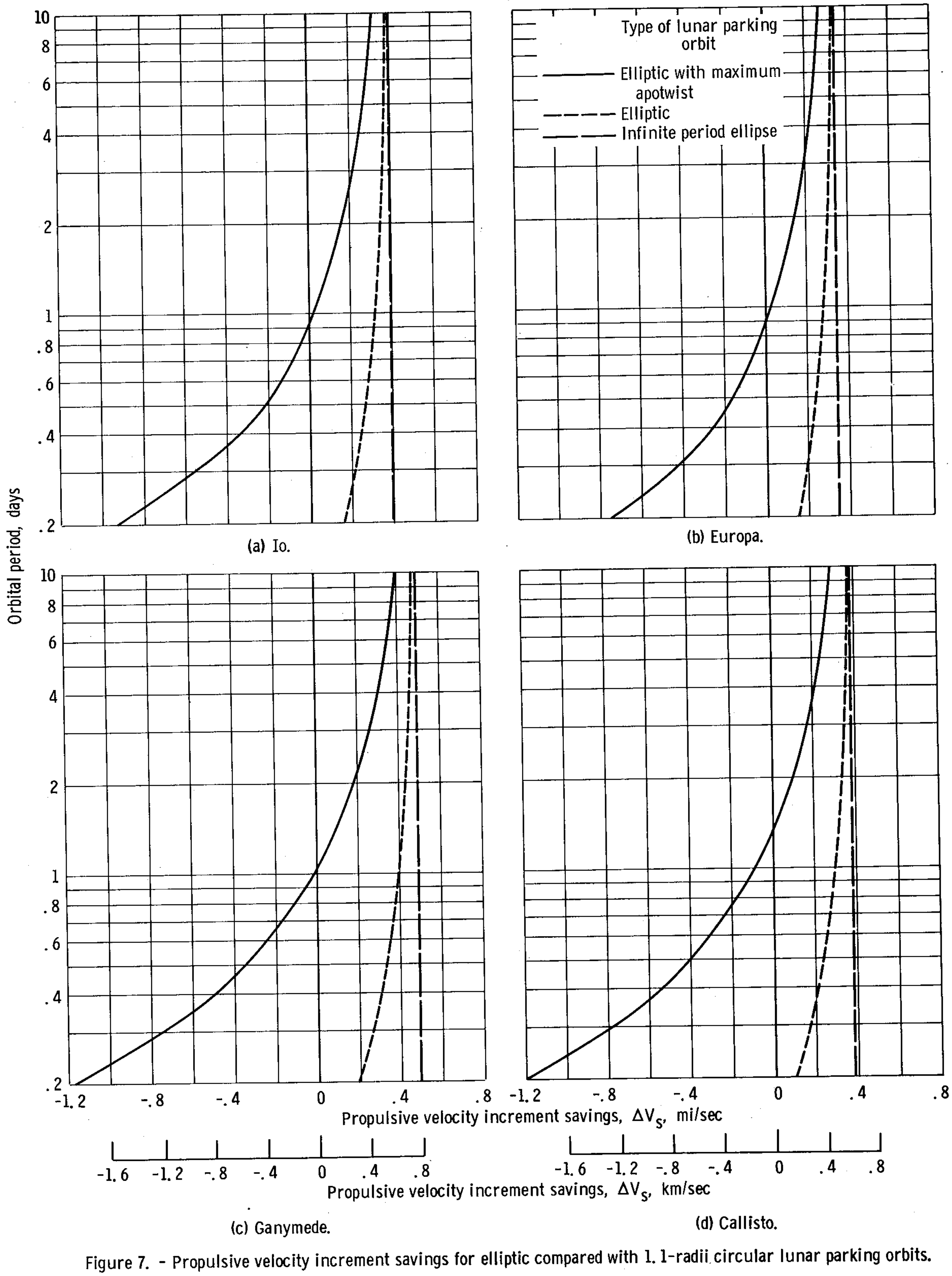


Figure 7. - Propulsive velocity increment savings for elliptic compared with 1.1-radii circular lunar parking orbits.

TABLE V. - PROPULSIVE VELOCITY INCREMENTS AND TIMES FOR INTERLUNAR PHASE OF LUNAR ORBITING STOPOVER MISSIONS

[Lunar sequence, IV-III-II-I.]

Type of parking orbit	Interlunar total propulsive velocity increment, $\sum \Delta V_i$		Time,[a] days
	mi/sec	km/sec	
All-propulsive braking at moons			
1. 1-Radii circular, 0 stay time			
Favorable lunar positions	4.19	6.74	9.66
Unfavorable lunar positions	4.19	6.74	32.78
Parabolic	1.74	2.8	∞
Elliptic[b] (with apotwisting) at unfavorable lunar positions	2.18	3.5	42.2
Atmospheric braking at moons			
1. 1-Radii circular, 0 stay time			
Favorable lunar positions	2.03	3.27	9.66
Unfavorable lunar positions	2.03	3.27	32.78
Parabolic	.41	.66	∞
Elliptic[b] (with apotwisting) at unfavorable lunar positions	.81	1.3	42.2

[a]Time to travel from Callisto (IV) to Io (I).
[b]Elliptic orbit period equal to stay time. Stay time, approximately 2.25 days at each moon.

summarized in table V. All-propulsive and atmospheric braking maneuvers are shown. The types of lunar parking orbits considered are 1.1-radii circular and "parabolic" (the two limiting cases) and elliptic.

Two times are given for the circular parking orbit. The minimum time corresponds to zero lunar stay time and assumes that the moons are in the most favorable position for the interlunar transfers. The minimum time is then the sum of the three interlunar transfer times between the pairs of moons as given in table IV. The worst-lunar-positions time is also for zero stay time and corresponds to just missing a favorable launch opportunity between each pair of moons. It is thus the sum of the three transfer times plus the three synodic periods between the pairs of moons. The parabolic lunar parking orbit implies an infinite lunar and Jupiter stay time.

The interlunar time for the elliptic orbit case is 42 days, a time that was selected to be greater than that for the worst lunar positions. The elliptic orbits have a period equal to the lunar stay time, and the lunar stay times are assumed to be approximately equal.

The apotwist maneuver is used to achieve the proper orientation of the ellipses for interlunar transfers. The parabolic orbit gives the lower limit in ΔV for lunar elliptic capture. Table V shows that the elliptic parking orbits selected also give most of this potential advantage in ΔV over the low circular orbit.

Atmospheric braking at the moons would greatly reduce the propulsive velocity increment requirements. The significance of this result depends on the existence of lunar atmospheres.

Lunar Orbiting Stopover Missions Without a Jupiter Parking Orbit

Choice of arrival and departure maneuver. - The best interlunar transfer sequence has already been determined to be the IV-III-II-I sequence. This sequence means that the best arrival maneuver is that maneuver which allows the lunar vehicle to enter an orbit at Callisto (IV) and depart from an orbit about Io (I), for a minimum propulsive velocity increment.

It is only necessary to consider the velocity increments which must be applied to the vehicle in Jupiter's sphere of influence, because the Earth departure date and the outbound transfer time are fixed to yield a constant value for the propulsive velocity increment to depart Earth orbit. The correct orientation for the Jupiter departure trajectory is obtained by selecting the proper lunar stay time.

Three arrival and departure methods are considered in this study: the single-impulse, double-impulse, and triple-impulse methods, as illustrated in figure 8. The apoapsis of the triple-impulse maneuver (fig. 8(c)) was selected to be 69.5 Jupiter radii. (This apoapsis is for a 25-day-period ellipse about Jupiter.) The total velocity increments and times required to arrive at or, by symmetry, to depart from each of the four moons by these three methods are summarized in table VI. For the four-moon stopover mission, the primary interest is in arrival at moon IV and departure from moon I. The other moons are included to permit consideration of a variety of missions.

The single-impulse method yields the lowest time, which begins from the Jupiter periapsis of the arriving Earth-Jupiter trajectory. In each case, the triple-impulse method requires the lowest total propulsive velocity increment to arrive at a moon. However, this low velocity increment is coupled with a long arrival time.

The total time for arrival at Callisto and departure from Io by triple-impulse maneuvers is $31.5 + 26.3 = 57.8$ days. For a 100-day stay time, this leaves 42 days for the lunar-exploration interlunar transfers. This time is larger than the total transfer time required for unfavorable lunar positions (table V) and is approximately the time selected for the lunar elliptic parking orbit case. Thus, the long transfer time associated with the triple-impulse maneuver appears acceptable.

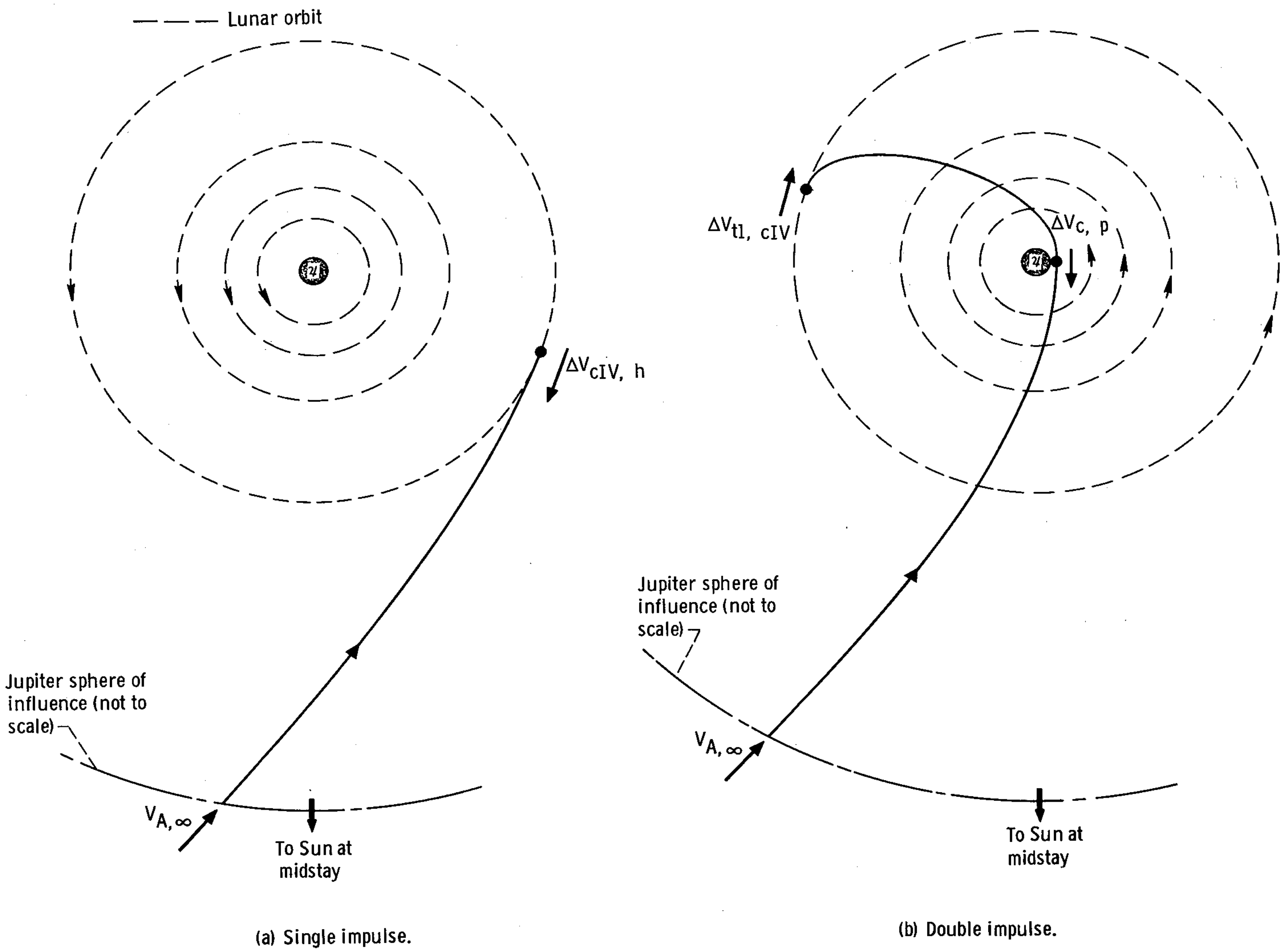
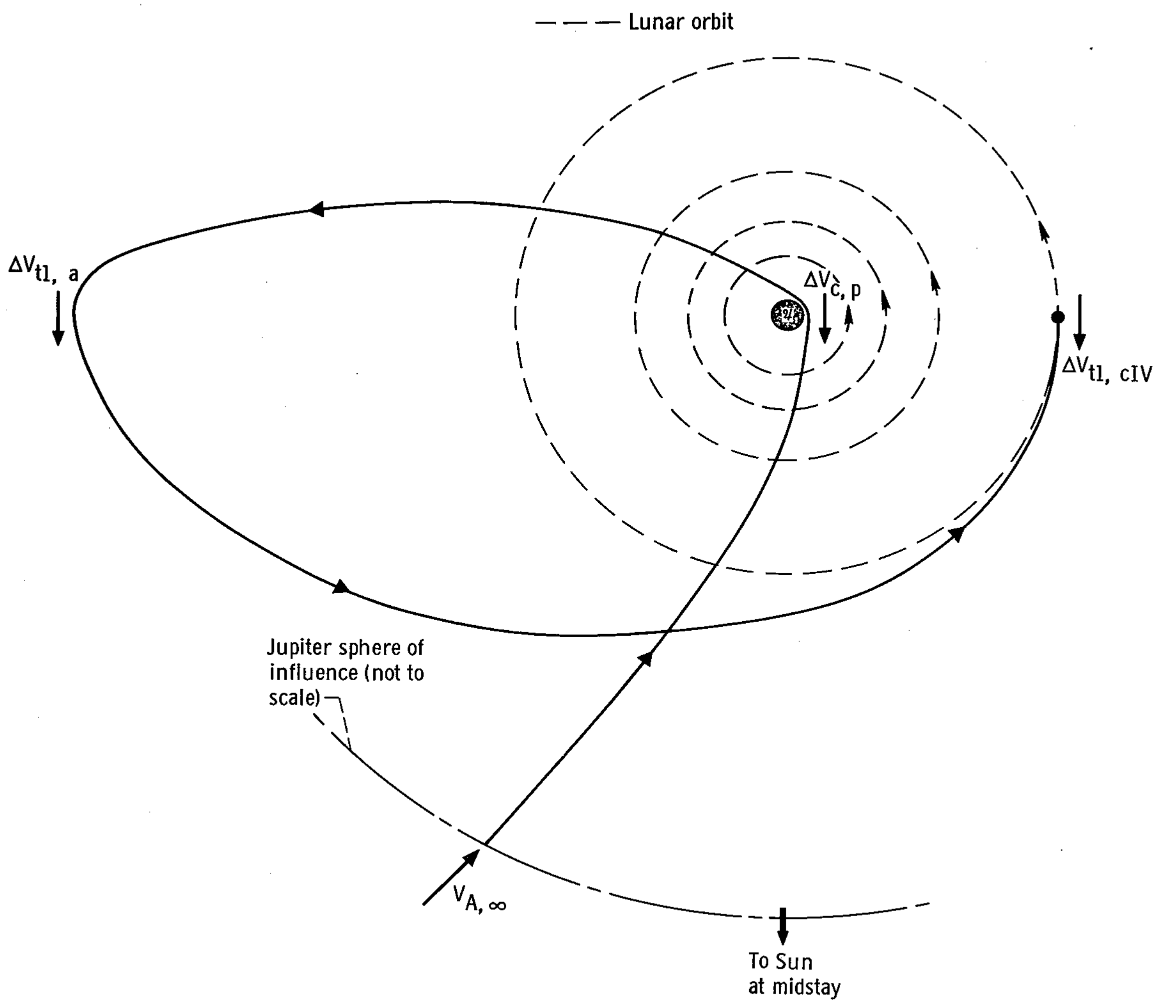


Figure 8. - Direct arrival (or departure) maneuvers for lunar orbiting stopover mission.



(c) Triple impulse.

Figure 8. - Concluded.

TABLE VI. - PROPULSIVE VELOCITY INCREMENTS AND TIMES FOR DIRECT ARRIVAL (OR DEPARTURE) MANEUVERS FOR LUNAR ORBITING STOPOVER MISSIONS WITH 1. 1-LUNAR-RADII PARKING ORBITS AT THE MOONS

[Mission time, 1000 days; stay time, 100 days.]

Moon	Sum of propulsive velocity increments from Jupiter sphere of influence to capture into 1. 1-radii circular orbit at first moon						Single-impulse[a] maneuver	Double-impulse[b, c] maneuver	Triple-impulse[d, e] maneuver
	Single-impulse[a] maneuver		Double-impulse[b, c] maneuver		Triple-impulse[d, e] maneuver		Time from Jupiter periapsis to first moon, days		
	mi/sec	km/sec	mi/sec	km/sec	mi/sec	km/sec			
Io (I)	6.38	10.3	8.13	13.1	5.03	8.09	0	0.403	26.3
Europa (II)	6.15	9.89	7.12	11.46	4.38	7.05	0	.736	27.5
Ganymede (III)	5.8	9.33	5.89	9.48	3.91	6.29	0	1.41	29.0
Callisto (IV)	6.08	9.78	4.96	7.98	3.78	6.08	0	3.14	31.5

[a]Fig. 8(a).
[b]Fig. 8(b).
[c]Periapsis at 1.1 Jupiter radii.
[d]Fig. 8(c).
[e]Periapsis at 1.1 Jupiter radii; apoapsis at 69.5 Jupiter radii.

If the stay time at Jupiter were sufficiently short to exclude the triple-impulse maneuver, for instance, only several days more than that required for the lunar exploration and interlunar transfers, the best of the single- or double-impulse maneuvers should be selected. In this case, a minimum $\sum \Delta V$ results from a double-impulse arrival at Callisto and a single-impulse departure from Io. The sum of the arrival and departure times in this case is 3.1 days. The $\sum \Delta V$ is 11.4 miles per second (18.3 km/sec) compared with 8.8 miles per second (14.2 km/sec) when the triple-impulse maneuver is used.

In the two cases just described, there is a reduction in arrival plus departure maneuver time of 54.7 days for an increase in the maneuver $\sum \Delta V$ of 2.6 miles per second (4.2 km/sec). From figure 3 of reference 1, there is an increase in the Earth departure ΔV of 0.25 mile per second (0.4 km/sec) for an increase in stay time at Jupiter from 50 to 100 days. (The 50-day increase corresponds to a 25-day decrease in one-leg transfer time, fig. 3, ref. 1). Based on these ΔV values the 100-day stay at Jupiter gives a trip with a lower $\sum \Delta V$ than does a 50-day stay. These results support the selection of the 100-day stay time.

Complete trips. - The characteristics of complete lunar orbital missions with total times of 1000 days and a 100-day stay are given in table VII. The interlunar sequence is IV-III-II-I. The arrival at Callisto and the departure from Io are by triple-impulse ma-

TABLE VII. - FOUR-MOON LUNAR ORBITING STOPOVER MISSIONS WITH DIRECT ARRIVAL

[Mission time, 1000 days; stay time, 100 days; triple-impulse arrival and departure; lunar sequence, IV-III-II-I.]

Type of braking at moons	Propulsive velocity increment, ΔV										Transfer[c] phase	Interlunar phase	Total
	Interplanetary phase				Transfer[a] phase, $\sum \Delta V_{t1} + \sum \Delta V_{t2}$		Interlunar[b] phase, $\sum \Delta V_i$		Mission total, $\sum \Delta V$		Maneuver time, days		
	Earth departure $\Delta V_{d,\oplus}$		Jupiter capture and escape $\Delta V_{c,p} + \Delta V_{e,p}$										
	mi/sec	km/sec	mi/sec	km/sec	mi/sec	km/sec	mi/sec	km/sec	mi/sec	km/sec			
Propulsive	5.2	8.37	2.44	3.93	5.74	9.24	2.18	3.5	15.56	25.04	57.8	42.2	100
Atmospheric	5.2	8.37	2.44	3.93	5.44	8.75	.81	1.30	13.89	22.35	57.8	42.2	100

[a]Transfer from elliptic apoapsis to Callisto plus transfer from Io back to elliptic apoapsis.
[b]Elliptic lunar parking orbits; orbital period equal to stay time.
[c]Time from Jupiter periapsis to Callisto plus time from Io back to Jupiter periapsis.

neuvers. The interlunar time is longer than that required if the moons are in the most unfavorable positions for each transfer. Elliptic parking orbits are assumed at the moons and the $\sum \Delta V$ value for this phase of the trip assumes nearly equal stay times at the four moons. The Earth-departure ΔV is also listed. The mission $\sum \Delta V$ is 15.56 miles per second (25.04 km/sec). This $\sum \Delta V$ is reduced to 13.89 miles per second (22.35 km/sec) if atmospheric braking could be used at the moons in the interlunar phase.

Lunar Stopover Missions From Jupiter Parking Orbit

Choice of Jupiter parking orbit and apsides for transfers to and from interlunar phase. - The major factors which must be considered when choosing the Jupiter parking orbit for the lunar stopover mission are the same as those discussed in the section Lunar Flybys From Jupiter Parking Orbit. Again a 25-day elliptical Jupiter parking orbit with a 1.1-Jupiter-radii periapsis is selected. With the Jupiter parking orbit specified, it is possible to expand table IV (p. 20); it lists the propulsive velocity increments for low circular parking orbits and for the limiting case of an infinite period elliptic lunar parking orbit and the times required for the various interlunar transfers but can be expanded to include the same information for transfers from the parking orbit apsides to the various moons. The results are listed in table VIII. This expansion was done to discover the best method for transferring from the parking orbit to Callisto and from Io back to the parking orbit. The characteristics of the transfers from Io to the parking orbit periapsis and apoapsis are given at the intersections of the row of Io and the columns for parking orbit periapsis and apoapsis, respectively.

The data of table VIII show that the best transfers for Io or Callisto are those that originate and terminate at the parking orbit apoapsis and thus yield an overall interlunar

TABLE VIII. - INTERLUNAR TRANSFER POSSIBILITIES FOR LUNAR ORBITING STOPOVER MISSIONS FROM 25-DAY DIRECT-MOTION JUPITER PARKING ORBIT

[For retrograde parking orbit add 2.28 mi/sec (3.67 km/sec) to mission ΔV.]

Depart from -	Arrive at -																		Definition
	Jupiter parking orbit periapsis			Io (I)			Europa (II)			Ganymede (III)			Callisto (IV)			Jupiter parking orbit apoapsis			
	mi/sec	km/sec	days	mi/sec	km/sec	days	mi/sec	km/sec	days	mi/sec	km/sec	days	mi/sec	km/sec	days	mi/sec	km/sec	days	
Jupiter parking orbit periapsis				6.62	10.65	-----	5.63	9.06	------	4.38	7.05	-----	3.49	5.77	-----				(a)
				6.23	10.17	-----	5.28	8.49	------	3.89	6.26	-----	3.1	4.99	-----				(b)
				-----	-----	-----	------	-----	------	-----	-----	-----	-----	----	-----				(c)
				-----	-----	0.403	------	-----	0.736	-----	-----	1.4	-----	----	3.14				(d)
				-----	-----	-----	------	-----	------	-----	-----	-----	-----	----	-----				(e)
Io (I)	6.62	10.65	-----				1.57	2.53	------	2.75	4.42	-----	3.82	6.15	-----	3.81	6.13	----	(a)
	6.23	10.17	-----				.836	1.34	------	1.86	3.0	-----	3.04	4.89	-----	3.46	5.57	----	(b)
	----	-----	-----				.825	1.32	------	1.55	2.49	-----	2.34	3.76	-----	----	----	----	(c)
	----	-----	0.403				-----	-----	1.31	-----	-----	2.09	-----	----	4.0	----	----	13.8	(d)
	----	-----	-----				-----	-----	4.83	-----	-----	4.44	-----	----	5.98	----	----	----	(e)
Europa (II)	5.63	9.06	-----	1.57	2.53	-----				1.33	2.14	-----	2.32	3.75	-----	3.16	5.08	----	(a)
	5.28	8.49	-----	.836	1.34	-----				.496	.798	-----	1.59	2.56	-----	2.81	4.52	----	(b)
	----	-----	-----	.75	1.2	-----				.647	1.04	-----	1.33	2.14	-----	----	----	----	(c)
	----	-----	0.736	-----	-----	1.3				-----	-----	2.62	-----	----	4.66	----	----	15.0	(d)
	----	-----	-----	-----	-----	4.83				-----	-----	9.67	-----	----	9.17	----	----	----	(e)
Ganymede (III)	4.38	7.05	-----	2.76	4.42	-----	1.33	2.14	------				1.28	2.06	-----	2.69	4.33	----	(a)
	3.89	6.26	-----	1.86	3.0	-----	.496	.798	------				.404	.65	-----	2.19	3.52	----	(b)
	----	-----	-----	1.195	1.92	-----	.69	1.11	------				.694	1.12	-----	----	----	----	(c)
	----	-----	1.4	-----	-----	2.09	-----	-----	2.62				-----	----	5.74	----	----	16.5	(d)
	----	-----	-----	-----	-----	4.44	-----	-----	9.67				-----	----	18.28	----	----	----	(e)
Callisto (IV)	3.49	5.77	-----	3.82	6.15	-----	2.32	3.73	------	1.28	2.06	-----				2.56	4.12	----	(a)
	3.1	4.99	-----	3.04	4.89	-----	1.59	2.56	------	.404	.65	-----				2.17	3.49	----	(b)
	----	-----	-----	1.45	2.33	-----	.99	1.59	------	.59	.949	-----				----	----	----	(c)
	----	-----	3.14	-----	-----	4.0	-----	-----	4.66	-----	-----	5.74				----	----	19	(d)
	----	-----	-----	-----	-----	5.98	-----	-----	9.17	-----	-----	18.28				----	----	----	(e)
Jupiter parking orbit apoapsis				3.81	6.13	-----	3.16	5.08	------	2.69	4.33	-----	2.56	4.12	-----				(a)
				3.46	5.57	-----	2.81	4.52	------	2.19	3.52	-----	2.17	3.49	-----				(b)
				-----	-----	-----	-----	-----	------	-----	-----	-----	-----	----	-----				(c)
				-----	-----	13.8	-----	-----	15.0	-----	-----	16.5	-----	----	19				(d)
				-----	-----	-----	-----	-----	------	-----	-----	-----	-----	----	-----				(e)

[a] Sum of propulsive velocity increments required to leave one moon (or Jupiter parking orbit) and to arrive at next moon (or Jupiter parking orbit) with 1.1-lunar-radii parking orbits at moons.

[b] Sum of propulsive velocity increment required to leave one moon (or Jupiter parking orbit) and to arrive at next moon (or Jupiter parking orbit) with parabolic "parking" orbits at moons.

[c] Propulsive velocity increment required to leave one moon (or to leave Jupiter parking orbit). Atmospheric braking at next moon; 1.1-lunar-radii parking orbit at the moons.

[d] Transfer time between one moon (or Jupiter parking orbit) and next moon (or Jupiter parking orbit).

[e] Transfer time between each pair of moons plus one synodic period.

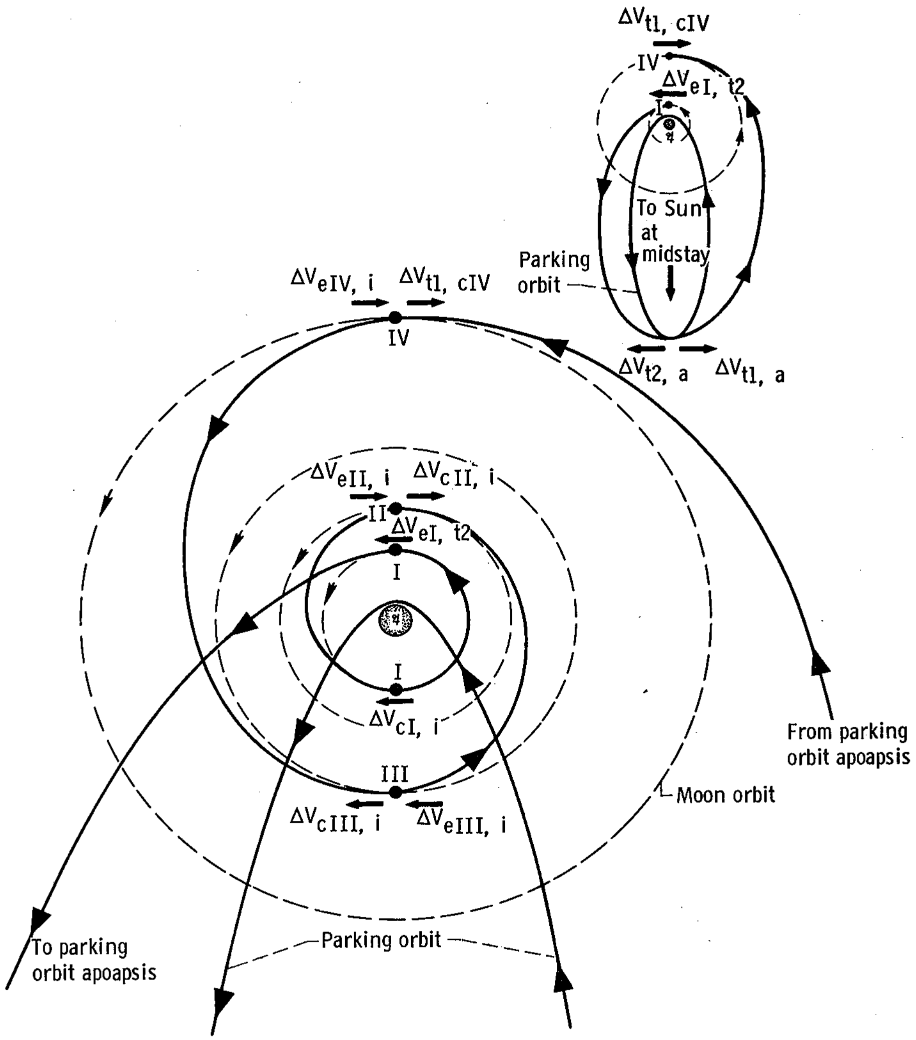


Figure 9. - Four-moon sequential lunar orbiting stopover mission from Jupiter 25-day direct-motion parking orbit. Lunar maneuver sequence, A-IV-III-II-I-A.

transfer sequence designated A-IV-III-II-I-A. This sequence is illustrated in figure 9.

Complete trips. - The characteristics of a complete lunar orbital mission starting from a 25-day-period Jupiter parking orbit are given in table IX. The parking-orbit-apse - moon sequence is A-IV-III-II-I-A. Again, the total trip time is 1000 days, the stay time is 100 days, and elliptic parking orbits are used at the moons. Several constituent propulsive velocity increments are listed. The parking orbit direction of motion reversal is the ΔV to reverse the parking orbit from retrograde to direct motion at arrival and back to retrograde motion at departure. The propulsive velocity increments to transfer from the parking orbit apoapsis to Callisto and from Io to the parking orbit apoapsis are listed under transfer phase (table IX). Next, the interlunar phase $\sum \Delta V$'s for elliptic lunar parking orbits are listed. Finally, the mission $\sum \Delta V$ is 19.54 miles per second (31.45 km/sec). This total is reduced to 17.87 miles per second (28.75 km/sec) if atmospheric braking at the moons is hypothesized.

TABLE IX. - FOUR-MOON LUNAR ORBITING STOPOVER MISSIONS FROM 25-DAY JUPITER PARKING ORBIT

[Mission time, 1000 days; stay time, 100 days; lunar maneuver sequence, A-IV-III-II-I-A (see fig. 9).]

Type of braking at moons	Propulsive velocity increment, ΔV												Parking orbit direction of motion reversals	Transfer[a] phase	Interlunar phase	Total
	Interplanetary phase				Parking orbit direction of motion reversals, $2\Delta V_{r,a}$		Transfer phase,[a] $\sum \Delta V_{t1} + \sum \Delta V_{t2}$		Interlunar phase,[b] $\sum \Delta V_i$		Mission total, $\sum \Delta V$		Maneuver time, days			
	Earth departure, $\Delta V_{d,\oplus}$		Jupiter capture and escape, $\Delta V_{c,op} + \Delta V_{e,op}$													
	mi/sec	km/sec	mi/sec	km/sec	mi/sec	km/sec	mi/sec	km/sec	mi/sec	km/sec	mi/sec	km/sec				
Propulsive	5.2	8.37	4.14	6.66	2.28	3.67	5.74	9.24	2.18	3.51	19.54	31.45	25.0	32.8	42.27	100.07
Atmospheric	5.2	8.37	4.14	6.66	2.28	3.67	5.44	8.75	.81	1.30	17.87	28.75	25.0	32.8	42.27	100.07

[a]Transfer from parking orbit apoapsis to Callisto plus transfer from Io back to parking orbit apoapsis.

[b]Elliptic lunar parking orbits; orbital period equal to stay time.

It was implied in the previous discussion that a single vehicle visited each of the moons in the IV-III-II-I sequence. It was also implied, for a specific instance, that fuel that is required for the transfer from moon II to moon I is decelerated at moon IV, and reaccelerated and then decelerated to transfer it to moon III, and finally accelerated and decelerated again to transfer it to moon II. The mission can be designed to avoid this needless acceleration of the auxiliary fuel. The mission would proceed in the following manner: When the direct-motion parking orbit is first established at the apoapsis, the interlunar vehicle with the crew and a propulsion module is launched toward Callisto (IV). At the same time, unmanned tankers are sent toward Ganymede, Europa, and Io, where they are captured in parking orbits the same as those to be acquired by the interlunar vehicle. Each tanker contains the fuel for escape from that moon and capture at the next moon. The interlunar vehicle with the crew and the propulsion module rendezvous with the tanker at each moon to refuel for the transfer to the next moon.

The advantage in ΔV with a refueling system as compared with carrying all the fuel in a single interlunar vehicle is illustrated in table X. The $\sum \Delta V$ to move the fuel from

TABLE X. - EFFECT OF TANKER USE ON PROPULSIVE VELOCITY INCREMENT TO DELIVER FUEL INTO POSITION FOR VARIOUS TRANSFERS

[25-Day direct-motion Jupiter parking orbit; lunar maneuver sequence, A-IV-III-II-I-A; 1.1-radii circular lunar parking orbits.]

Transfer	Tanker vehicle		Interlunar vehicle	
	Total propulsive velocity increment to deliver fuel into position for specified transfer			
	mi/sec	km/sec	mi/sec	km/sec
Io to parking orbit apoapsis	3.81	6.13	6.57	10.57
Europa to Io	2.84	4.57	4.62	7.43
Ganymede to Europa	2.20	3.54	3.28	5.28

the Jupiter parking orbit to the moon from which a transfer is to be made is compared for a tanker refueling vehicle and a single interlunar vehicle, for several transfers. The greatest saving in $\sum \Delta V$ for fueling is in the transfer from Io to the parking orbit apoapsis, where the $\sum \Delta V$ for the tanker to arrive at Io is 3.81 miles per second (6.13 (6.13 km/sec) or 58 percent of that required for the single interlunar vehicle. A trade-off between weight saving and increased complexity remains to be evaluated, but that evaluation is beyond the scope of this report.

Mission to fewer moons. - The previous calculations considered visits to four moons. The effect of this assumption is illustrated in table XI, which shows the propulsive velocity increments for visits to fewer moons. The results shown are for the interlunar $\sum \Delta V$ starting from a 25-day Jupiter parking orbit and for the limiting case of parabolic parking orbits at the moons. Rows 2 and 3 compare the $\sum \Delta V$ when the visit to Europa, the smallest of the four moons, or to Io, the innermost moon, is omitted. There is a distinct advantage to eliminating Io, the moon deepest in the "gravity well" of Jupiter. Thus, if three moons are to be visited, the sequence is A-IV-III-II-A. Similarly, for two- and one-moon missions, the sequences are A-IV-III-A and A-IV-A. The $\sum \Delta V$ values and times are also given in table XI. The $\sum \Delta V$ is reduced by about 50 percent for the interlunar and transfer phases of the mission by changing from a four-moon to a Callisto-only stopover mission.

TABLE XI. - EFFECT OF NUMBER OF MOONS VISITED ON INTERLUNAR PHASE AND TRANSFER PHASE PROPULSIVE-VELOCITY-INCREMENT SUM, AND ON TIMES FOR LUNAR ORBITING STOPOVER MISSIONS

[25-Day direct-motion Jupiter parking orbit; favorable lunar positions.]

Trajectory	Propulsive velocity increments, $\sum \Delta V_{t1} + \sum \Delta V_i + \sum \Delta V_{t2}$				Maneuver[a] time
	1.1-Radii circular orbits		Parabolic orbits		days
	mi/sec	km/sec	mi/sec	km/sec	
A-IV-III-II-I-A	10.5	16.9	7.36	11.8	43.81
A-IV-III-I-A	10.4	16.7	7.89	12.7	41.08
A-IV-III-II-A	8.33	13.4	5.88	9.46	42.81
A-IV-III-A	6.53	10.5	4.76	7.66	45.57
A-IV-A	5.12	8.24	4.34	6.98	38.00

[a]Does not include time required for retrograde-direct reversals (required reversal times are P to P trajectories, 50 days; P to A trajectories, 37.5 days; A to A trajectories, 25 days).

Summary of Results for Lunar Stopover Missions

For four-moon visits, the sequence of visitation that gave the lowest total propulsive velocity increment was IV-III-II-I (i.e., from the outermost moon, Callisto, to the innermost moon, Io).

If no Jupiter parking orbit is used and the total stay time is 100 days, the triple-impulse arrival and departure maneuver gives the lowest $\sum \Delta V$.

If a Jupiter parking orbit is used, the lowest $\sum \Delta V$ results if the transfer to the first moon and from the last moon is made with the parking orbit apoapsis as one terminal of the transfer. The total propulsive velocity increments for several lunar orbiting missions are summarized in table XII.

For both the direct and parking orbit modes, the use of elliptic parking orbits at the moons instead of low circular orbits offers about a 12-percent reduction in mission $\sum \Delta V$. If atmospheric braking can be used in the interlunar phase, a further reduction in $\sum \Delta V$ is possible. (At present the existence of lunar atomsphere is uncertain.)

Comparison of the direct and parking orbit modes indicated that the former mode gives about an 18 percent lower $\sum \Delta V$. However, the parking orbit mode offers several weight-reducing possibilities by reducing the ΔV for part of the mission loads. The interlunar vehicle can be refueled from tankers sent to the inner moons from the parking orbit. Also the Earth-deceleration and Jupiter-escape stages can be stored in the park-

TABLE XII. - SUMMARY OF RESULTS FOR FOUR-MOON LUNAR ORBITING STOPOVER MISSIONS

[Mission time, 1000 days; stay time, 100 days.]

Type of mission	Interlunar sequence	Moons visited	Propulsive velocity increment, ΔV												Definition
			Interplanetary phase				Parking orbit direction of motion reversals, $2\,\Delta V_{r,a}$		Transfer phase $\sum \Delta V_{t1} + \sum \Delta V_{t2}$		Interlunar phase, $\sum \Delta V_i$		Mission total, $\sum \Delta V$		
			Earth departure, $\Delta V_{d,\oplus}$		Jupiter capture and escape, $\Delta V_c + \Delta V_e$										
			mi/sec	km/sec	mi/sec	km/sec	mi/sec	km/sec	mi/sec	km/sec	mi/sec	km/sec	mi/sec	km/sec	
Arrival and departure by triple-impulse method	IV-III-II-I	All four major moons	5.2	8.37	2.44	3.93	----	----	6.37	10.2	4.19	6.74	18.2	29.2	(a)
			5.2	8.37	2.44	3.93	----	----	5.74	9.24	2.18	3.5	15.56	25.04	(b)
			5.2	8.37	2.44	3.93	----	----	5.44	8.75	.81	1.3	13.89	22.35	(c)
25-Day Jupiter parking orbit	A-IV-III-II-I-A	All four major moons	5.2	8.37	4.14	6.66	2.28	3.67	6.37	10.2	4.19	6.74	22.18	35.64	(a)
			5.2	8.37	4.14	6.66	2.28	3.67	5.74	9.24	2.18	3.51	19.54	31.45	(b)
			5.2	8.37	4.14	6.66	2.28	3.67	5.44	8.75	.81	1.3	17.87	28.75	(c)
25-Day Jupiter parking orbit	A-IV-A	Callisto	5.2	8.37	4.14	6.66	2.28	3.67	5.12	8.25	----	----	16.74	26.94	(a)
Arrival and departure by triple-impulse method	A-IV-A	Callisto	5.2	8.37	2.44	3.93	----	----	5.12	8.25	----	----	12.76	20.54	(a)

[a]Circular lunar parking orbits; all-propulsive braking.
[b]Elliptic lunar parking orbits; all-propulsive braking; elliptic period equal to stay time.
[c]Elliptic lunar parking orbits; atmospheric braking; elliptic period equal to stay time.

ing orbit until needed. In the direct modes, these stages must be carried through the interlunar transfers.

Visiting one rather than four moons can reduce the $\sum \Delta V$ for the total mission by about 25 percent when low circular parking orbits and propulsive braking are used.

Multiship Mission

The preceeding discussion dealt primarily with the trajectories in the vicinity of Jupiter and its moons. While it is possible for all components of a manned round-trip mission to travel the same interplanetary trajectory (e.g., the 1000-day trip with 100 days stay), it is not necessary that they do so. It is possible to select trajectories for some of the components which have lower total propulsive velocity increments than the manned phase and thus reduce the total initial weight required in Earth orbit. An example of such a multiship manned round trip is shown in figure 10, and the corresponding

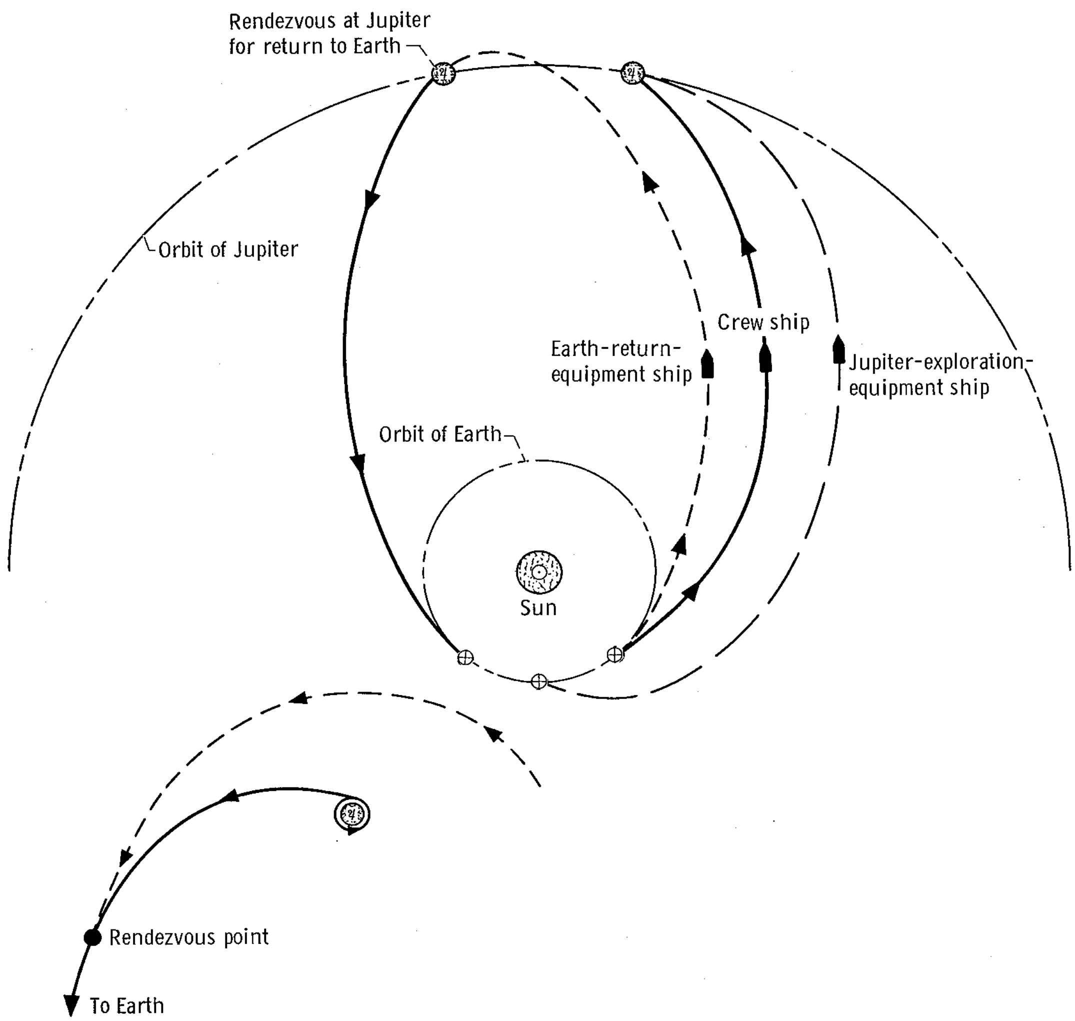


Figure 10. - Three-ship Jupiter round trip.

TABLE XIII. - COMPARISON OF THE SEVERAL PARTS OF

THREE-SHIP JUPITER MISSION[a]

Mission part	Total propulsive velocity increment, $\sum \Delta V$	
	mi/sec	km/sec
Crew-ship 450-day outbound leg to retrograde 25-day Jupiter parking orbit (outbound leg only)	7.27	11.7
Earth-return-equipment ship, hyperbolic-rendezvous-trajectory, 1000-day nonstop round trip	6.0	9.65
Jupiter-exploration-equipment ship, 790-day outbound leg to 25-day retrograde elliptic parking orbit at Jupiter	5.6	9.0
Lunar-excursion-vehicle $\sum \Delta V$ from and return to 25-day parking orbit apoapsis; retrograde to direct-motion reversals	[b]10.2 [c]7.4	16.4 11.9

[a]See fig. 10.
[b]Four-moon visit.
[c]Visit to Callisto.

$\sum \Delta V$ for each phase is given in table XIII. The concept employs three separate ships. The first ship is unmanned and carries the Jupiter exploration system; it is sent from Earth to a Jupiter parking orbit by a low-energy, 790-day-long trajectory. The second ship, bearing the crew, is launched 340 days later on a higher-energy, 450-day-long trajectory and arrives simultaneously at Jupiter with the first vehicle to rendezvous with it. A third unmanned vehicle carrying the Earth-return system is launched from Earth to execute a nonstop flyby of Jupiter. The launch date is selected so that the vehicle passes Jupiter at the end of the 100-day stay of the crew. As it flys by, the crew carries out a rendezvous with it and returns to Earth. As the data of table XIII show, the trajectory for each unmanned system has a lower $\sum \Delta V$ than that for the crew ship. The multiship mission described could require a lower weight in Earth orbit than the single-ship mission.

The $\sum \Delta V$ for a four-moon interlunar exploration is given in the last row for comparison with the interplanetary $\sum \Delta V$. Elliptic lunar parking orbits are assumed. This $\sum \Delta V$ is about the same as that for the interplanetary flight.

CONCLUDING REMARKS

An analysis was made of a wide variety of trajectories to four moons of Jupiter for a total mission time of 1000 days and 100 days stay at Jupiter. While a mission analysis with specified mission objectives and payloads is required to draw conclusions about what are the best trajectories, the following general observations about what trajectories are favorable appear justified based on the present $\sum \Delta V$ analysis.

In table XIV, a series of Jupiter lunar missions is listed in the general order of increasing mission $\sum \Delta V$ and decreasing velocity of the vehicle past the moons. This passage velocity is assumed to indicate the inverse of the observation time available. The general point is that an increase in observation time and in the number of moons visited requires increased $\sum \Delta V$, when the total mission time is fixed at 1000 days. The lowest $\sum \Delta V$ occurs for a nonstop flyby of Jupiter, and this mission can be timed to include the passage of one moon. If excursion vehicles are sent from this main vehicle to fly by the three remaining moons, the most difficult moon to visit requires a mission $\sum \Delta V$ 23 percent greater than that for the simple Jupiter - single-moon flyby. Doing

TABLE XIV. - COMPARISON OF JUPITER LUNAR ROUND TRIPS WITH ATMOSPHERIC BRAKING AT EARTH RETURN AND ELLIPTIC PLANETARY PARKING ORBITS

Mission	Trip time, days	Stay time, days	Total propulsive velocity increment for mission, $\sum \Delta V$		Lunar passage velocity	
			mi/sec	km/sec	mi/sec	km/sec
Jupiter flyby or Jupiter - four-moon flyby with favorable lunar positions	1000	0	6.0	9.65	10 to 20	16 to 32
Jupiter - four-moon flyby with unfavorable lunar positions; most difficult moon	1000	0	7.39	11.9	10 to 20	16 to 32
Four-moon lunar flyby from periapsis of 25-day Jupiter parking orbit	1000	100	16.82	27.07	3 to 7	5.3 to 11.3
Jupiter - four-moon lunar orbiting stopover mission with direct triple-impulse arrival and departure, elliptic lunar parking orbits	1000	100	15.56	25.04	1.2 to 1.7	1.9 to 2.7
Jupiter - four-moon lunar orbiting stopover mission with direct triple-impulse arrival and departure; low circular lunar parking orbits	1000	100	18.2	29.2	0.8 to 1.2	1.3 to 1.9
Mars-orbiting round trip	420	40	6.1	9.82	---------	----------
Venus-orbiting round trip	445	40	4.64	7.48	---------	----------

the lunar flybys from a Jupiter parking orbit markedly increases the $\sum \Delta V$ but reduces the passage velocity. The lunar stopover mission with elliptic parking orbits at the moons and direct arrival at and departure from the moons requires a $\sum \Delta V$ slightly less than that for the lunar flyby from a Jupiter parking orbit. This method also reduces passage velocities. Going from elliptic to low circular parking orbits increases the $\sum \Delta V$ but further reduces the passage velocity. Thus, the general trend of increasing $\sum \Delta V$ with decreasing passage velocity is evident.

While at the outset of this study the 100-day stay at Jupiter was somewhat arbitrarily chosen, this stay time proved compatible with the required interlunar transfer times plus the arrival and departure maneuver times. When a parking orbit is required about Jupiter, one with a 25-day period was found to be appropriate. While retrograde-motion Jupiter parking orbits yield the lowest interplanetary propulsive velocity increments, a direct-motion orbit is a better one from which to initiate visits to the moons. The reversal from retrograde to direct-motion parking orbits can be made at the ellipse apoapsis.

The following conclusions are based on the desirability of achieving a low $\sum \Delta V$:

1. The parking orbit periapsis is the best position on the Jupiter parking orbit from which to initiate lunar flybys, if a parking orbit is used.

2. For lunar orbital visits, the best sequence in which to visit the moons is sequentially from the outer moon to the inner moon.

3. If the lunar orbital visits are initiated and terminated from a Jupiter parking ellipse, the apoapsis of the parking ellipse is the most favorable terminal.

4. For direct arrival and departure from lunar orbital visits, the triple-impulse maneuver gave the lowest $\sum \Delta V$ but the longest maneuver time.

The last two rows in table XIV present the $\sum \Delta V$ for typical fast Mars and Venus round-trip missions using elliptic parking orbits. The trip times shown for trips to these two planets are about half that for the Jupiter trip, although 1000-day Mars trips are also being considered. The $\sum \Delta V$ for the Mars and Venus missions are about comparable to those for the Jupiter flyby or the interplanetary legs of the Jupiter stopover trips.

While a trajectory analysis can point to many interesting mission profile possibilities and can give an indication of the favorable way to accomplish a mission, a final evaluation must depend on a mission study which has specified mission objectives and which includes the calculation of system weights and the considerations of system complexity and reliability.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 7, 1967,
121-30-02-01-22.

APPENDIX - SYMBOLS

A apoapsis of ellipse about Jupiter

e eccentricity of orbit

N integer

P periapsis of ellipse about Jupiter

V velocity, mi/sec (km/sec)

V' adjusted velocity at sphere of influence (see figs. 2 to 4), mi/sec (km/sec)

ΔV propulsive velocity increment, mi/sec (km/sec)

$\sum \Delta V$ summation of propulsive velocity increments, mi/sec (km/sec)

β propulsive turning at sphere of influence, deg

η true anomaly on Jupiter parking orbit of Jupter capture or escape maneuver

θ total planetocentric turning angle required at Jupiter, deg

μ gravitational parameter, mi^3/sec^2 (km^3/sec^2)

ψ_b heliocentric travel angle inbound to Earth, deg

ψ_o heliocentric travel angle outbound to Jupiter, deg

I Io

II Europa

III Ganymede

IV Callisto

⊙ Sun

⊕ Earth

♃ Jupiter

Subscripts:

A arrive

a at apoapsis of elliptic orbit about Jupiter

c to capture about Jupiter

cI to capture about Io

cII to capture about Europa

cIII to capture about Ganymede

cIV to capture about Callisto

d depart

e to escape from Jupiter

eI to escape from Io

eII to escape from Europa

eIII to escape from Ganymede

eIV to escape from Callisto

fI to flyby Io

fII to flyby Europa

fIII to flyby Ganymede

fIV to flyby Callisto

h at periapsis of Jupiter-centered hyperbolic trajectory

i interlunar phase; refers to maneuvers occurring after arrival at first moon but before departure from last moon. Applies to both flyby and stopover trajectories op off periapsis maneuver at Jupiter capture and escape that minimizes $\Delta V_c + \Delta V_e$

p at periapsis of elliptic orbit about Jupiter

r reverse direction of Jupiter-centered elliptical orbit for retrograde-direct-motion reversals

s propulsive velocity increment savings

t1 initial transfer phase; maneuvers to transfer from direct-motion ellipse about Jupiter to interlunar phase

t2 terminal transfer phase; maneuvers to transfer from interlunar phase to direct-motion ellipse about Jupiter

∞ at Jupiter sphere of influence

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