EFFECT OF MISSION MODE AND ORBIT ECCENTRICITY ON UNMANNED OUTER PLANET CAPTURE MISSIONS





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ABSTRACT

The performance advantages of employing elliptic capture orbits for unmanned missions to Jupiter, Saturn, Uranus, and Neptune are investigated. As part of this investigation, the relative merits of the direct flight mode and the Jupiter swingby mode of heliocentric transfers are compared. A method of presentation is shown that permits the effects of trip time, capture orbit eccentricity, and transfer mode to be evaluated. It is shown that, depending on the weight to be placed in planetary orbit, definite trip time - orbit eccentricity regions exist within which either transfer mode is superior.

## INTRODUCTION

The purpose of this study is twofold. The first is to investigate the advantages of employing elliptic capture orbits for unmanned missions to Jupiter, Saturn, Uranus, and Neptune. The second is to compare the benefits of employing these capture orbits for two heliocentric trajectory modes - the direct mode and the Jupiter swingby mode. While the specific numerical results presented in this paper are of interest, they are of limited value because they depend on assumptions concerning launch vehicle and propulsion system characteristics. The method developed to present the results, however, is general and can be applied to planning studies for other systems.

Direct trips require extremely long trip times, 3 to 20 years or more, for reasonable Earth departure velocity requirements. These trip times can be significantly reduced, by a factor of 2 to 3, if Jupiter swingbys are used. The swingby missions, however, require high capture velocity increments for the shortest trip times since the arrival velocity vectors intersect the planet heliocentric velocity vectors at very large angles. Consequently, the swingby missions have, in the past, only been considered attractive in the context of target planet flybys.

For the orbital stopover missions, elliptic capture orbits offer a significant energy saving since they considerably reduce the insertion velocity requirements from those required for circular orbits. Because of the large masses of the outer planets, the velocity reduction can be of such magnitude that, for a given vehicle system, trip times significantly shorter than those associated with minimum energy transfers can be achieved. This trend applies to both the direct and swingby modes.

The results of the mission analysis are summarized in the two following sections. Next, the system characteristics that were assumed are discussed, followed by a presentation of the final results of the study. These results are shown as curves of minimum attainable capture orbit eccentricity as a function of trip time for each planet and mission mode. Two values of orbiting payload weight are considered as well as two types of planet orbit insertion propulsion system. The conclusions of the study are presented in the last section.

## SELECTION OF LAUNCH OPPORTUNITY

During any time period of several years, energy requirements for direct missions to the outer planets vary only slightly between successive opportunities. This is primarily due to the small change in the angular positions of the planets. The heliocentric orbits of the planets are almost circular and lie near the plane of the ecliptic so that the planetary configurations are relatively unchanged.

The next opportunity for Jupiter swingby missions to the outer planets occurs during the 1976 to 1981 time period. The Jupiter swingbys are more sensitive to angular variations than the direct missions since the position of Jupiter relative to both the Earth and the destination planet must be considered. For a launch year near the best Jupiter swingby opportunity, however, the comparison of the direct and swingby mode will be indicative of the results for other available launch years.

The nominal launch year selected for each planet (Jupiter, 1978; Saturn, 1977; Uranus, 1979; Neptune, 1979) was based on the data presented in Ref. 1. It should be noted that, during the 1977 launch opportunity, Saturn is near its maximum latitude so that the velocity requirements for a near-Hohmann transfer are quite severe. This situation, however, exists throughout a launch period of several years so that, even in this case, the effect of launch year need not be considered explicitly.

## TRAJECTORY SELECTION

Minimum-energy trajectories were selected for a range of trip times. The selections were based on circular capture orbits with a fixed periapsis radius for each planet. Penalties to provide for Earth launch windows were not included. These trajectories also yield minimum energy when eccentric orbits are employed since the velocity savings for higher eccentricities (assuming periapsis insertion at a fixed pericenter radius) are independent of the arrival conditions. This velocity saving is simply the difference between circular and eccentric orbit velocity, and therefore, depends only on the periapsis radius. In this study, periapsis radius was assumed constant for each planet, independent of mission mode.

With the proper selection of a nominal periapsis radius, the effect of the assumption of a constant radius on the results is not significant. If low periapsis values (i.e., about 1.1 planet radii) were selected, the effect on the velocity requirements would be significant, but near the optimum periapsis radius (i.e., the periapsis radius for which the insertion velocity is a minimum for a given orbit eccentricity and hyperbolic excess speed), these requirements tend to be insensitive to periapsis radius. The optimum radius itself, however, can vary significantly even for a fixed hyperbolic excess speed. For example, with an arrival excess speed of 0.3 emos (Earth mean orbital speed, 29.8 km/sec) at Jupiter, the optimum periapsis radius for circular orbit is 45 planet radii, but for a 0.9 eccentric orbit the optimum radius is only 2 radii. Yet a selection of some average value for the nominal periapsis radius is justified, since the percentage increase in velocity requirements is generally small although the difference between the optimum and nominal periapsis radii is large.

The specific values of pericenter radius chosen are

| | |
|---|---|
| Jupiter, | 10 planet radii |
| Saturn, | 6 planet radii |
| Uranus, | 2 planet radii |
| Neptune, | 2 planet radii |

Slightly higher nominal values could have been selected (i.e., 15 planet radii at Jupiter) without a significant variation in the velocity requirements. But the orbital periods even for slightly higher periapsis distances can become unreasonably large at high eccentricities. Therefore, low periapsis values were selected whenever possible. The orbit periods for the nominal periapsis values selected do not exceed about 40 days at 0.7 eccentricity.

Characteristic velocity requirements* for each planet and mission mode are shown in Table 1 for several trip times. The selected trip times are intended to indicate the variation in velocity requirements in the region considered. For the Jupiter, Saturn, and Uranus direct missions, minimum energy trips are shown, but for the Uranus swingby and Neptune missions, only trips up to 18 and 20 years, respectively, are given. It should be noted that the velocity requirements for Jupiter and Saturn do not decrease smoothly as trip time increases since there is a slight cusp when the heliocentric transfer (Earth to Jupiter leg for a swingby) changes from type I to type II. The total velocity increase is, however, slight. Trip times associated with the minimum type I and type II and the peak between type I and type II are given in the table for Jupiter and Saturn. Also note that neither the direct nor the Jupiter swingby mode has consistently lower velocity requirements for the entire range of trip times considered. The direct mode is optimum only for the shorter trip times, while the swingby mode has lower total velocity requirements for longer trip times. The Earth departure velocity requirements are, however, consistently lower for the swingby mode.

## ECCENTRIC ORBIT VELOCITY REDUCTIONS

Figure 1 illustrates the velocity reduction available by employing eccentric capture orbits. This velocity reduction is the difference between the velocity increment required to obtain a circular orbit with the selected pericenter radius and the velocity requirement for an eccentric orbit with this same pericenter radius. Circular capture requirements for the outer planet missions generally vary between 5 and 12 km/sec, depending on the trip time, planet, and mission mode. The velocity reduction obtained by employing a 0.7 eccentric orbit is 3 to 4 km/sec, so that the capture requirements can be reduced by as much as 80%. This represents a significant reduction in the characteristic velocity requirements and indicates the potential advantages of elliptic capture orbits.

*The total characteristic velocity requirement is the sum of the circular Earth orbit velocity and the incremental velocity requirements at Earth orbit departure and circular planet orbit insertion.

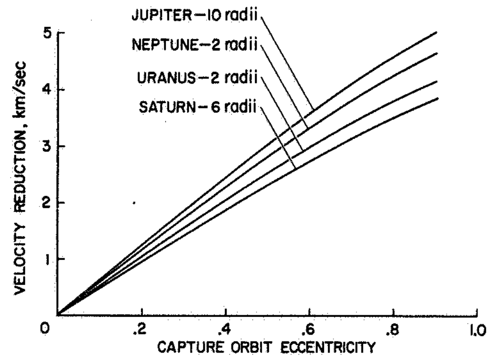



Fig. 1. Velocity Reduction Obtained by Employing Elliptic Orbits

## SYSTEM DESCRIPTION

In the following paragraphs are presented the characteristics of the vehicle systems and other nontrajectory items necessary to proceed with the analysis.

### Payload

Two representative payload weights, 500 and 5500 lb, are examined. The 500-lb payload is indicative of a minimum orbiter class mission, while the 5500-lb payload represents a more advanced system with the capability perhaps of atmospheric probes, subsatellites, etc. In each case, this represents the gross spacecraft weight (i.e., scientific payload and payload support subsystem) injected into planet orbit. It does not include the inert weight of the planet orbit insertion stage nor does it include the adapter weight between the stage and the payload. (This adapter weight is assumed to be 5% of the gross spacecraft weight.)

### Midcourse Velocity Requirements

A 100 m/sec midcourse requirement is included for each leg of the mission, i.e., 100 m/sec for a direct mission and 200 m/sec for a Jupiter swingby mission.

### Meteoroid Environment

A nominal meteoroid environment is assumed here. The specific details concerning the meteoroid model are related in Ref. 2.

### Earth Launch Vehicle

One launch vehicle, the Saturn V/Centaur, is investigated. A performance curve showing payload versus characteristic velocity is given in Fig. 2. The Centaur is considered to be jettisoned after Earth departure so that a separate planet orbit insertion stage is required.

### Planet Orbit Insertion Propulsion Systems

Two systems are examined since the capture stage may have a significant effect on the specific results of the comparison. The first of these is assumed to be an Earth storable system ($N_2O_4$/A-50) with a specific impulse of 305 sec. The second system assumed is a space storable system ($FLOX/CH_4$)

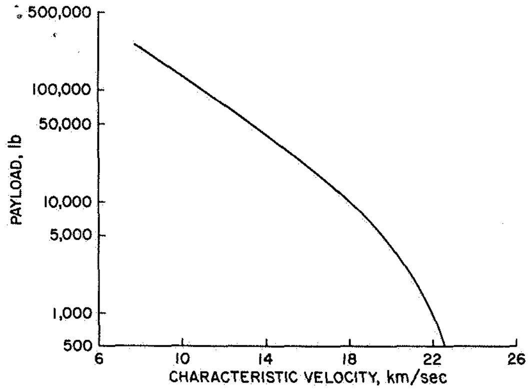



Fig. 2. Saturn V/Centaur Performance

with a specific impulse of 405 sec. In each case, an optimized stage was employed with a structural weight based on current technology (see Ref. 3 for development of the weight scaling equations).

## ANALYSIS

In comparing the two trajectory modes, the overall effect the trajectory mode will have on the mission objective should be considered. For outer planet orbiters, the most critical mission parameters are trip time and payload. Since higher payload weights are usually only possible with longer trip times, it is necessary to determine the variation of these parameters for the two trajectory modes. Capture orbit eccentricity is also being considered since any velocity savings due to elliptic payload capture at planet arrival can be traded essentially for additional payload capability. The capture orbit effects will vary considerably for the two modes due to the differences in circular orbit insertion velocities. This implies that the velocity reduction, and hence payload increase, will not be proportional for the two modes.

Employing the trajectory data and system characteristics, the spacecraft weight requirements immediately after Earth departure (i.e., Centaur payload) were determined for several planet orbit eccentricities and mission durations. Curves such as those illustrated in Fig. 3 were generated to summarize this data. This figure shows the spacecraft weight after Earth departure as a function of capture orbit eccentricity for several mission durations.

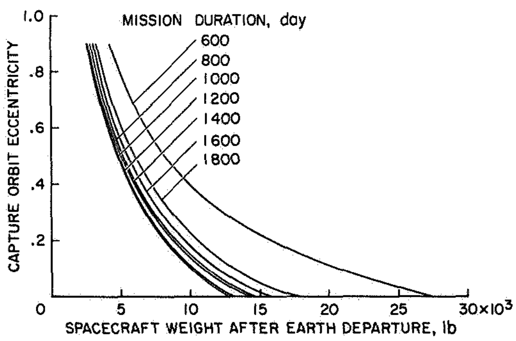



Fig. 3. Spacecraft Weight vs. Capture Orbit Eccentricity; Jupiter Direct, Space Storable Propellant - Payload 500 lb

To determine the minimum attainable orbit eccentricity for a given trip time, it is necessary to compare Figs. 2 and 3. Since each trip time is associated with a unique minimum characteristic velocity at Earth departure, the Centaur payload capability can be determined from Fig. 2. Then, by equating the spacecraft weight requirement from Fig. 3 with the Centaur payload capability from Fig. 2, a minimum attainable capture orbit eccentricity is obtained for the specific mission. Higher eccentricities are, of course, possible, but these would not result in maximum utilization of the launch vehicle. Curves of minimum capture orbit eccentricity versus mission duration are thus developed. The results are summarized in Figs. 4 to 7.

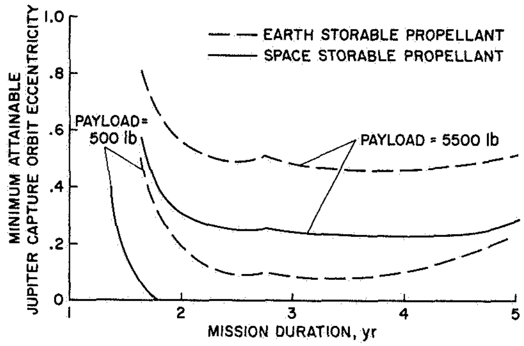
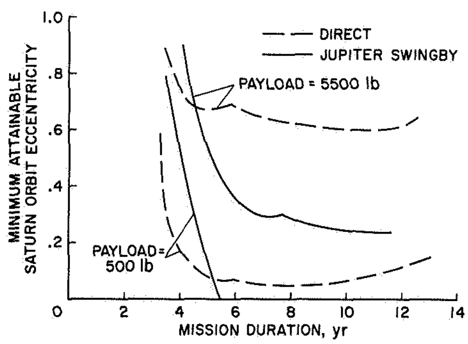
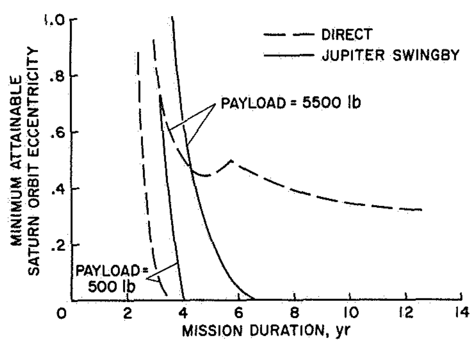



Fig. 4. Capture Orbit Eccentricity vs. Mission Duration; Jupiter Direct

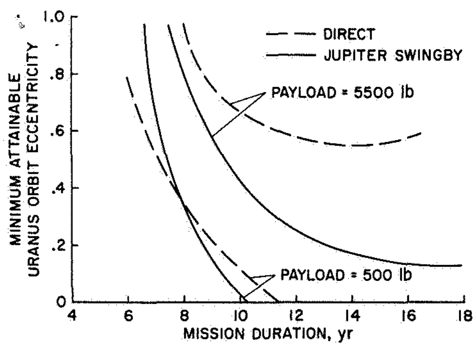



(a) Earth Storable Propellant

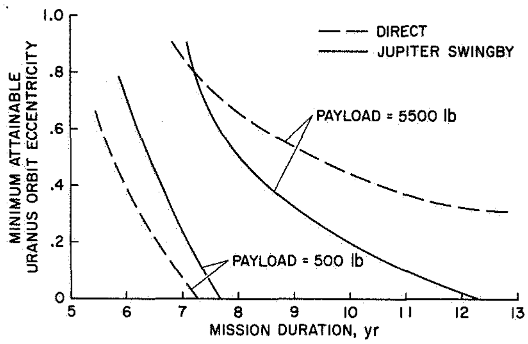



(b) Space Storable Propellant

Fig. 5. Capture Orbit Eccentricity vs. Mission Duration; Saturn

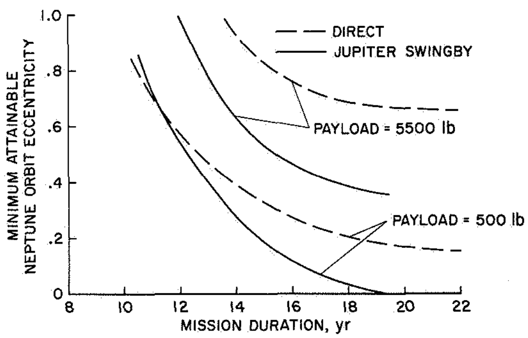



(a) Earth Storable Propellant

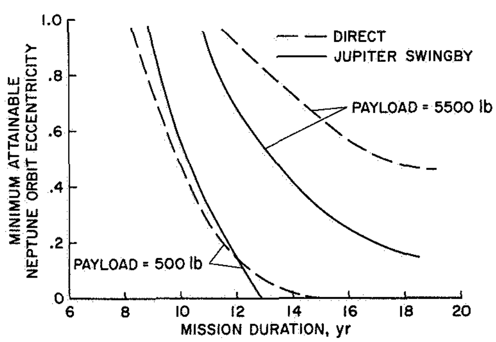



(b) Space Storable Propellant

Fig. 6. Capture Orbit Eccentricity vs. Mission Duration; Uranus




(a) Earth Storable Propellant




(b) Space Storable Propellant

Fig. 7. Capture Orbit Eccentricity vs. Mission Duration; Neptune

## RESULTS

For unconstrained trip times, the results indicate that there is a definite trade-off between the Jupiter swingby mode and the direct mode both with respect to total characteristic velocity requirements and capture orbit eccentricity. Referring first to the velocity requirements, a trip time usually exists that separates the region for which the direct mode has lower velocity requirements from the low velocity region for the Jupiter swingby mode. As previously indicated, the swingbys are more desirable for longer missions. If a flyby maneuver is employed at planet encounter rather than a capture maneuver, this separation of regions does not occur; the swingby mode is always more favorable for a flyby. This contrast is reasonable, however, since flybys include only the Earth departure characteristic velocity requirements which are consistently lower for the Jupiter swingby mode. The orbiters, however, also include planet capture requirements which are lower for the swingby missions only at the longer trip times. Hence, for an orbiter, there will be some trip time that separates the optimum regions for the direct and swingby mode.

Considering the effect of capture orbit eccentricity on the mode comparison, it can generally be asserted that the swingby mode permits lower orbit eccentricities for the heavier payload while the direct mode is somewhat better for the lighter 500-lb payload. The reason for this trade-off is apparent from a consideration of the velocity requirements. For the heavy payload, the propulsion systems considered here are not capable of performing the short missions (due to the high velocity requirements of both the direct and swingby missions). At the longer trip times, where the system performance capability is not exceeded, the swingbys, as previously indicated, have lower velocity requirements than the direct. Therefore, the swingby mode is generally optimum for the 5500-lb payload. For the light payload, however, the region of system capability occurs at the shorter missions where the direct mode has slightly lower velocity requirements. Hence, the direct mode is usually optimum for the light payload. It should thus be noted that the particular payload weight for which the swingbys become optimum will vary with the system capability.

The analysis also indicates that eccentric capture orbits can significantly increase the applicability of specific launch vehicle and propulsion systems to the outer planet missions. For example, as shown in Fig. 4, it is not possible to achieve a circular capture orbit at Jupiter with the Earth storable propulsion system. But by employing a slightly eccentric orbit ($e = 0.15$), it is possible to achieve an 800-day transfer with a 500-lb payload.

The differences between the two orbit insertion propulsion systems considered are significant. The main benefit of the higher specific impulse is either to reduce the trip time or decrease the minimum attainable orbit eccentricity. The choice of propulsion system can affect the mode comparison for specific trip times or orbit eccentricities, but it does not appear to significantly affect the general conclusions.

## CONCLUSIONS

In view of the above discussion, the conclusions can be summarized as follows:

(1) A mission duration usually exists that separates the region for which the direct mode has lowest velocity requirements from the region for which the Jupiter swingby mode has the lowest requirements.

(2) The swingby mode is generally optimum for heavier payloads, while the direct mode is usually optimum for lighter payloads.

(3) Eccentric capture orbits can significantly increase the applicability of specific boosters and propulsion systems to outer planet missions.

(4) Any increase in the capability of the orbit insertion propulsion system can be used to reduce the mission duration or decrease the capture orbit eccentricity.

## REFERENCES


[1]Deerwester, J. M., "Jupiter swingby missions to the outer planets," Journal of Spacecraft and Rockets, Vol. 3, No. 10, October 1966.

[2]Savin, R. C., "Sensitivity of long-duration manned spacecraft design to environmental uncertainties," Aviation and Space, Progress and Prospects, pp. 1-7.

[3]"Study of trajectories and upper-stage propulsion requirements for exploration of the solar system," United Aircraft Corporation Research Laboratories Rept. E-910352-9 (July 1966) (Contract NAS2-2938).


TABLE 1 VELOCITY REQUIREMENTS

| Destination | Direct | | | Jupiter Swingby | | |
|---|---|---|---|---|---|---|
| | Trip Time, year | Total[(a)] ΔV | Earth[(b)] Escape ΔV | Trip Time, year | Total ΔV | Earth Escape ΔV |
| Jupiter | 1.75 | 22.05 | 14.82 | --- | --- | --- |
| | 2.40 | 20.92 | 14.65 | --- | --- | --- |
| | 2.75 | 21.10 | 15.00 | --- | --- | --- |
| | 3.60 | 20.75 | 14.52 | --- | --- | --- |
| | 4.50 | 20.95 | 14.42 | --- | --- | --- |
| Saturn | 3.00 | 23.55 | 16.10 | 3.00 | 26.50 | 15.37 |
| | 5.00 | 21.60 | 16.27 | 6.70 | 19.45 | 14.75 |
| | 5.90 | 21.90 | 16.60 | 7.60 | 19.60 | 14.95 |
| | 11.00 | 21.00 | 15.35 | 11.00 | 19.10 | 14.75 |
| | 15.00 | 21.50 | 15.60 | 14.00 | 19.30 | 14.75 |
| Uranus | 6.00 | 25.30 | 16.80 | 6.00 | 26.10 | 15.20 |
| | 8.00 | 22.80 | 16.12 | 8.00 | 21.95 | 14.76 |
| | 13.00 | 21.20 | 15.80 | 12.00 | 19.30 | 14.65 |
| | 18.00 | 21.70 | 16.20 | 16.00 | 18.90 | 14.55 |
| Neptune | 8.00 | 29.70 | 18.10 | 8.00 | 30.05 | 15.68 |
| | 12.00 | 24.10 | 16.65 | 12.00 | 23.10 | 14.75 |
| | 16.00 | 22.45 | 16.23 | 16.00 | 20.60 | 14.65 |
| | 20.00 | 21.80 | 16.05 | 20.00 | 19.70 | 14.65 |

[a]Sum of the circular Earth orbit velocity and the incremental velocity requirements at Earth orbit departure and circular planet orbit insertion

[b]Sum of the circular Earth orbit velocity and the Earth orbit departure incremental velocity requirements