MULTIPLE ASTEROID FLYBY MISSIONS

DAVID R. BROOKS AND WILLIAM F. HAMPSHIRE II
NASA Langley Research Center

The use of spacecraft for studying the physical properties of the asteroid belt can be approached in several ways. Certainly the simplest approach is to send a spacecraft into the asteroid belt and measure the effects of the environment encountered; this has the advantage of not requiring a vehicle to be targeted to any particular destination. With such an approach, properties may be obtained for those classes of objects that are populous enough to provide a significant number of encounters within the measurement range of the spacecraft. Unfortunately, the large asteroids do not constitute such a class of objects; the probability of an undirected spacecraft passing within measurement range of an asteroid having a diameter of 1 or more km is negligible.

For studying the properties of the large asteroids as a class, as opposed to studying one particular asteroid, it is clear that a way must be found to sample the population of large asteroids by studying more than one, preferably with the same equipment on the same mission. This task requires the assumptions that the position of likely targets can be predetermined with sufficient accuracy and that the spacecraft has onboard guidance and propulsion for maneuvering to preselected positions in space and time. It is assumed that the permanently numbered asteroids (presently 1748 in *Ephemeris,* 1971) is the group of objects from which minor planet targets will be chosen, because the assignment of a permanent number to an asteroid usually denotes a reasonably well-known ephemeris based on numerical integration of osculating orbital elements.

It is the purpose of this paper to define various types of multiple asteroid flyby missions involving the 1748 numbered asteroids, to determine the magnitude of impulsive Δv demands for performing typical missions, and to relate these requirements to spacecraft capabilities planned or envisioned for other applications. A particular goal of the study is to identify possible multiple flyby missions whose in-flight propulsive requirements are attainable with reasonably sized chemical systems, rather than being so large as to make advanced propulsion schemes necessary or highly desirable for effective spacecraft performance. The idea of searching for close asteroid encounters that can be obtained with small Δv maneuvers is not new. Bender (1967) has conducted a similar study in a search for cis-Martian asteroid encounter opportunities; and the desirability of multiple flyby missions has been mentioned recently by several authors involved in solar electric mission analysis (Archer, 1970; Brooks, 1970; Wrobel and Driver, 1969).

RANDOM ENCOUNTERS WITH LARGE ASTEROIDS

It was stated in the introduction that the probability of a spacecraft encountering large asteroids by chance was negligible. Deferring for a moment the definition of "encounter," this statement can be justified easily. Actual count of the 1748 numbered asteroids shows that at any given time an average of about 431 are contained in a washer-shaped volume having an inside radius of 1.8 AU, an outside radius of 3.7 AU, and a thickness of 0.2 AU, centered about the ecliptic plane. If these asteroids are assumed to be uniformly distributed in the volume, $\pi(3.7^2 - 1.8^2)0.2$ AU^3, and to have, on the average, velocities equal to the circular velocity, the number of encounters to be expected by a spacecraft in this volume for a time $t_2 - t_1$ is

$$N = \frac{431}{6.56} \pi R_E^{\;2} \int_{t_1}^{t_2} \left| \mathbf{v}_{SC} - \mathbf{v}_C \right| dt \tag{1}$$

where $\mathbf{v}_{SC}$ and $\mathbf{v}_C$ are the spacecraft and circular velocity vectors and $\pi R_E^{\;2}$ is the constant cross-sectional area of a spherically symmetric encounter volume of radius R_E about the spacecraft.

The question of what R_E must be to result in a useful encounter cannot and need not be answered exactly. Bender (1967) assumed that the closest distance of approach should be less than 2×10^4 km for telescopic observation. For asteroid mass determinations based on perturbations of a spacecraft's velocity, passage distances are required that range from 10^3 km for smaller numbered asteroids to as much as 10^6 km for Ceres (Meissinger, 1971, personal communication). For the purposes of obtaining a number from equation (1), assume that the largest radius at which useful data can be obtained is $R_E = 10^{-4}$ AU (1.5×10^4 km). For this radius, a spacecraft in a 1 by 3 AU orbit in the ecliptic will encounter an average of only 6×10^{-6} asteroids per orbit.

Accounting for all those asteroids that could be observed from Earth and cataloged along with the present 1748 numbered asteroids will improve, of course, the chances of a random encounter. However, even if the total number of large asteroids is as high as 10^5, the sample trajectory given above will still yield only 3×10^{-4} encounters per orbit–an increase of about 50 times above the previous result. An encounter radius as large as 0.1 AU, on the other hand, should result in about six encounters with the numbered asteroids per orbit for the same trajectory.

The pertinent conclusion to be drawn from the foregoing discussion is that a spacecraft must be maneuvered to result in close encounters with the numbered asteroids because the radius of the sphere in which encounters are likely to take place (0.1 AU) is large compared to the distance required for a measurement (10^{-4} AU). It is a good approximation to assume that a spacecraft must be guided to hit the target asteroid.

MISSION ANALYSIS

Multiple asteroid flyby missions that involve maneuvering a spacecraft away from a nominal trajectory with onboard propulsion may be categorized as follows:

(1) Opportunities resulting from randomly generated trajectories that combine flybys of several asteroids, none of which are preselected, into one mission requiring a small total Δv for maneuvering
(2) Multiple flyby missions that are required to include particular asteroids of known scientific interest; for example, Ceres
(3) Missions to major planets that include favorable opportunities for maneuvering close to one or more asteroids

Additional categories might involve circularizing the spacecraft orbit in the asteroid belt or rendezvous with a major asteroid. Such maneuvers require large values of Δv compared to those resulting from the present study of multiple flybys, hence they belong to a different type of mission that involves much larger spacecraft and an advanced propulsion system such as solar electric-ion engine propulsion.

The basic logic for examining multiple flyby missions is contained in a computer program that compares cartesian position coordinates of a spacecraft with the positions, at the same time, of the 1748 numbered asteroids. The asteroid positions are obtained by using the osculating elements in the 1971 *Ephemeris* volume as Kepler elements and by advancing the listed mean anomalies along unperturbed ellipses to the desired time. The positions so generated are considered to be exact for the purposes of this study. The spacecraft trajectory may be a Keplerian ellipse in the ecliptic, generated internally by the computer program, or an externally generated trajectory, as in the case of missions involving major planets. As the positions of spacecraft and asteroids are computed, their relative separations are compared against a preselected search radius, and all asteroids passing within the search radius are counted as possible targets for that particular mission. For a search radius of 0.1 AU, a sizable number of encounters can be expected on the average—about six, according to equation (1), for a trajectory to 3 AU.

To determine impulsive Δv requirements for multiple flyby missions, various asteroid flyby sequences are examined after possible targets are identified. First, the spacecraft is retargeted at Earth launch to intercept one of the asteroids. Then, an algorithm that solves Lambert's problem is utilized to

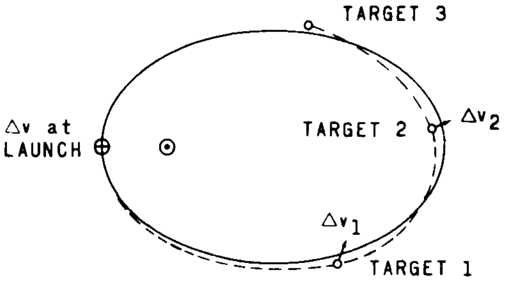

Figure 1.–Typical trajectory for a multiple asteroid flyby mission.

determine the impulsive Δv required for the spacecraft to encounter the second target at the time of closest approach to the second target. This process is then repeated as necessary to complete the desired sequence. The asteroids are assumed to be massless points that are intercepted exactly by the spacecraft. Figure 1 illustrates how the Δv maneuvers are performed for a three-asteroid sequence. The Δv required at Earth for the spacecraft to intercept the first target is assumed to be provided by the launch vehicle and is not charged against the capability of the spacecraft.

RESULTS

Random Search Trajectories

For spacecraft trajectories that are not constrained to intercept a major planet or some particular asteroid, a Keplerian ellipse in the ecliptic can be specified by the launch date and aphelion; the perihelion is assumed to be at the launch point. Table I shows a listing of asteroid encounters resulting from 11 such trajectories, launched between Julian dates 2444500 (late 1980) and 2445000 (early 1982) at 50 day intervals to an aphelion of 3 AU. The search radius is 0.1 AU. The number of encounters ranges from 8 to 15, and the average number is 10 per mission, as compared to the 6 per mission predicted by equation (1). The agreement between these two numbers is acceptable, considering the simplifying assumptions made in deriving equation (1) and the fact that the listings in table I are not sufficient to constitute a statistically significant sample.

Additional details concerning the seven closest encounters during the trajectory launched on Julian date 2444800 (mid-1981) are given in table II; this launch date yielded the largest number of different targets of the 11 launch dates shown in table I. The encounters take place over a time of 659 days, representing a range in spacecraft true anomaly of 115°. Certainly, it will not be possible, in general, to maneuver to all asteroids passing within 0.1 AU of a spacecraft. For example, consecutive flybys of all the asteroids listed in table II would require an impulsive Δv of 41.6 km/s, computed as indicated in

TABLE I.—*Numbered Asteroids Passing Within 0.1 AU of a Spacecraft in a 1 by 3 AU Orbit Launched on the Julian Date Shown*

Julian date, 244*XXXX*										
4500	4550	4600	4650	4700	4750	4800	4850	4900	4950	5000
548	255	797	1720	985	290	1515	1665	1019	1446	1601
1382	1130	770	1082	878	377	149	449	841	1729	1153
1153	1389	1300	1350	1727	1576	725	939	355	1448	248
1635	90	462	846	1704	1443	1110	1069	228	1293	557
834	1199	1383	732	1379	898	76	1462	787	1635	90
308	180	424	91	62	447	1674	243	1029	701	888
1053	647	1362	1382	1289	1645	1068	178	518	832	1085
1739	1064	1705	969	513	1357	870	317	996	1745	1337
	1270		810	632	62	1593	1225	1147	1562	497
				1741	1278	1740				518
				644	1056	479				
				220	1292	561				
						30				
						1720				
						822				

the previous section. When encounters with the spacecraft occur in relatively rapid succession (for example, 1515 → 149 and 1740 → 561 in table II), it will generally be required to make a choice between two targets. There are, however, several opportunities for flying close to three asteroids for a total impulsive Δv of less than 1 km/s; such missions are listed in table III. It is always assumed that the spacecraft is launched from Earth to intercept the first target in a multiple flyby sequence. All seven of the asteroids in table II are

TABLE II.—*Data for the Seven Closest Asteroid Encounters With a Spacecraft Launched on Julian Date 2444800 Into a 1 by 3 AU Orbit*

Asteroid no.	Julian date, 244*XXXX*	Radius, AU	True anomaly[a]	Minimum separation, 10^6 km	Relative velocity, km/s
1515	4971	1.97	118°	5.3	11.4
149	4980	2.02	121	5.4	11.1
1674	5134	2.72	154	6.7	8.3
870	5422	2.91	194	7.6	5.1
1740	5508	2.69	207	7.1	9.2
561	5528	2.63	211	4.0	10.5
1720	5630	2.16	233	2.8	12.3

[a] Of the spacecraft.

TABLE III.—*Impulsive Δv Requirements for Three-Asteroid Encounters Involving the Close Approaches Listed in Table II*

Encounter sequence[a]	Impulsive Δv, km/s
1515→1674→561	0.93
1515→870→1720	.79
1515→561→1720	.81
1515→1674→1740	.69
1515→1674→1720	.88
149→870→561	.93
149→870→1720	.58
1674→561→1720	.89

[a] Only those sequences for which the impulsive Δv is less than 1 km/s are listed.

included in one or more of the triple flybys listed in table III. A four-asteroid mission, 1515 → 1674 → 561 → 1720, is possible with a total impulsive Δv of only 0.8 km/s.

Trajectories to a Preselected Asteroid

For missions that are constrained to include a close flyby of a particular asteroid, a Keplerian ellipse in the ecliptic is still used for the spacecraft trajectory; but the launch date and aphelion are adjusted to include an encounter with the desired asteroid when it passes through the ecliptic. Data for generating trajectories to Ceres and Vesta are readily available in the NASA *Planetary Flight Handbook* (Lockheed Missiles & Space Co., 1966). As an example for this study, the trajectory resulting from a late 1975 launch to

TABLE IV.—*Data for the Five Closest Asteroid Encounters With a Spacecraft Constrained to Pass Near 1 Ceres During a 1975 Launch Opportunity*

Asteroid no.	Julian date, 244*XXXX*	Radius, AU	True anomaly[a]	Minimum separation, 10^6 km	Relative velocity, km/s
632	2956	2.37	131°	4.5	14.0
1435	2985	2.53	137	6.5	5.9
946	3260	2.30	174	5.7	4.6
947	3313	3.32	180	2.8	4.0
1	3568	2.83	212	5.3	9.8

[a] Of the spacecraft.

Ceres[1] was examined for other close asteroid approach opportunities. Data for the five closest approaches are summarized in table IV. They take place over a period of 612 days and a spacecraft true anomaly range of 81°. For the trajectory studied here, 1 Ceres was encountered last, but this would not be generally true. Of the several theoretically possible multiple asteroid missions for this trajectory, two triple flybys can be performed with an impulsive $\Delta\nu$ of less than 1 km/s: 632 → 946 → 1 with $\Delta\nu = 0.73$ km/s and 632 → 947 → 1 with $\Delta\nu = 0.24$ km/s.

Asteroid Encounters on Trajectories to Jupiter

The possibility of passing close to an asteroid enroute to a major planet provides extra motivation for performing the planetary mission if the required maneuvering can be assumed to have no significant effect on the primary mission goal. As an example of such a mission, a 1975 trajectory to Jupiter has been examined for close approaches to asteroids, and those passing within 0.1 AU are tabulated in table V. Of course, because of the relatively short time spent in the asteroid belt on this trajectory, there are not as many close approach opportunities as for the previous two mission types. Nevertheless, the encounter sequence 666 → 396 → Jupiter can be performed with an impulsive $\Delta\nu$ of only 0.52 km/s. It should be noted that the flyby velocities for this type of trajectory are necessarily higher than for trajectories having an aphelion in the asteroid belt.

TABLE V.—*Asteroid Encounters on a Trajectory to Jupiter Launched During a 1975 Opportunity*

Asteroid no.	Julian date, 244*XXXX*	Radius, AU	Minimum separation, 10^6 km	Relative velocity, km/s
1636	2734	1.97	12.9	16.7
666	2736	1.99	9.7	16.2
27	2751	2.12	8.6	18.0
396	2875	3.06	7.1	10.2

DISCUSSION OF RESULTS

It is clear that the $\Delta\nu$ results presented above should be taken only as representative of what can be expected for multiple asteroid flyby missions. Most important, computing asteroid positions from Kepler's equations does

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[1] Ceres has an aphelion of 2.9776 AU, a perihelion of 2.5574 AU, and an orbital inclination of 10°.6.

not make the best use of available data. However, a computer search for possible targets based on integrated orbits for all the asteroids would require excessive computation time. Once possible targets have been identified for a particular mission, the asteroid positions during encounters need to be recomputed from integrated orbits that take planetary perturbations into account. This will improve the position data to some extent, but it is certain that the actual Δv needed for a particular mission will require significant adjustments once attitude control is included and midcourse correction requirements are analyzed, based on spacecraft and asteroid ephemeris uncertainties.

The particular multiple flyby missions selected to serve as examples of various mission types are, like the Δv values, only representative of what can be expected. It is likely that better mission opportunities could be found if an extensive parametric survey of asteroid belt trajectories were undertaken. However, even the small number of trajectories presented in this study demonstrate that there is an abundant supply of multiple asteroid flyby missions that can be performed for less than 1 km/s, and it should be possible to keep within a Δv of 1 km/s for many missions even after guidance and attitude control requirements are satisfied. Thus, the results of this study indicate that the stated goal of identifying multiple asteroid flyby missions suitable for reasonably sized chemical systems can be achieved.

The quantitative meaning of "reasonably sized" can be made clear by relating the Δv requirements resulting from this study to representative requirements and capabilities of currently funded projects. It has been possible to find multiple asteroid missions involving flybys of two or three asteroids with impulsive Δv values between 0.1 and 1 km/s. (Flybys of more than three asteroids can be expected to require more Δv.) In table VI, the Δv range between 0.1 and 1 km/s is compared with Pioneer F and G and Viking spacecraft capabilities and also with the requirements for some representative interplanetary maneuvers, particularly those in the asteroid belt. It is of interest to note that the Δv for a loose Jupiter orbit (1.2 by 120 Jupiter radii) is about 0.7 km/s for v_∞ of 7 km/s, and this value lies within the range of multiple flyby requirements. The Pioneer F and G spacecraft have a Δv capability of about 0.2 km/s, of which only 0.1 km/s is available for maneuvering, but the possibility of uprating a Pioneer spacecraft for the Jupiter orbiter mission is being seriously studied by NASA Ames Research Center (Howard F. Matthews, 1971, personal communication). Such a spacecraft could just as well be used for the missions studied here. The Viking orbiter spacecraft also has ample propulsive capability for multiple flyby missions; about 1.5 km/s is required for Mars orbit insertion and subsequent orbit adjustments. Plane changes, circularizing, and rendezvous maneuvers in the asteroid belt require progressively more Δv, and some examples are given in table VI.

The mission analysis in this study has considered only the impulsive Δv values that can be delivered to a good approximation by chemical rockets; the

TABLE VI.–*Comparison of Multiple Flybys With Other Missions*

Mission	Impulsive Δv, km/s
Multiple flybys	0.1 to 1.0
Pioneers F and G[a]	0.1
Jupiter orbit[b]	0.7
Viking orbiter	1.5
Plane change at 3 AU:[c]	
5°	1.1
10°	2.1
Circularize:	
2 AU	3.8
4 AU	5.5
Ceres rendezvous	8.0 to 10.0
Solar electric propulsion (SEP), per 100 days[d]	0.3 to 0.5

[a] Does not include attitude control and midcourse guidance capability. Pioneers F and G may be uprated for use as Jupiter orbiters.

[b] 1.2 by 120 Jupiter radii, $v_\infty = 7$ km/s.

[c] From a 1 by 3 AU ellipse.

[d] At 3 AU.

performance of low-thrust systems, like solar electric-ion engine systems, are also of great interest. With SEP, the propulsive performance is limited not by the properties of the propellant (ionized mercury), as is the case with a chemical rocket, but by the available power and time. The initial acceleration of payload-optimized SEP spacecraft at 1 AU is generally between 0.3 and 0.5×10^{-6} km/s^2 (Brooks, 1970). At 3 AU, the available solar power is decreased by a factor of 9 and, at a constant radius of 3 AU, the velocity of an SEP spacecraft may be increased proportionally with time in the amount of 0.3 to 0.5 km/s for every 100 days of thrusting time. Therefore, multiple flyby missions for SEP spacecraft have to be chosen carefully to allow sufficient time intervals between one target and the next.

For this study, no attempt has been made to select asteroids on any basis other than their availability as low-energy targets. Clearly, such a determination should be made, and the foregoing results demonstrate that there are enough approximately equivalent mission opportunities to allow a selective approach in mission analysis. Apart from ranking asteroids in order of scientific interest, which is an important task in itself, the criteria that could be applied to an asteroid for the purpose of easing demands on a multiple flyby spacecraft are (1) low identification number, (2) low orbital inclination, and (3) asteroid near aphelion at encounter. The first criterion assumes that low number is associated with high mass and large size, thereby making mass determination and optical observation easier. The remaining two criteria serve to minimize the relative flyby velocity, thus making tracking easier during the encounter. The encounter duration, based on a minimum relative flyby velocity of about 5 km/s and an encounter radius of 10^{-4} AU, will be no greater than about 1.7 hr.

CONCLUSIONS

It has been shown that the probability of passing close enough to a large asteroid to allow performance of useful measurements is negligible. However, if a spacecraft is assumed to have some onboard propulsion for maneuvering close to an asteroid, many multiple asteroid flyby missions can be identified that require a total impulsive Δv of less than 1 km/s, and therefore lie within the capability of available chemical-propulsion systems. These include triple asteroid flybys that may involve a major asteroid such as Ceres and double asteroid flybys followed by a flyby of Jupiter. Compared with other useful maneuvers in the asteroid belt, multiple flybys require less impulsive Δv, and some of the triple flyby sequences require less impulsive Δv than a loose elliptical orbit around Jupiter. Spacecraft having suitable propulsive capability include the Viking orbiter and possibly the Pioneer spacecraft (which can be uprated for a Jupiter orbiter mission).

It is expected that the impulsive Δv results for particular missions will be affected significantly by midcourse and guidance requirements once these are analyzed; but the large number of apparently attractive missions indicates that it will still be possible to find missions that can be performed for less than 1 km/s. The large number of possible missions also indicates that asteroid targets can be selected on the basis of size and orbital properties to ease the problems of observation during the encounter.

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DISCUSSION

GEHRELS: If asteroid encounters are possible on trajectories to Jupiter, why have such missions not been included on Pioneers F and G, which were originally identified as asteroid/Jupiter missions?

BROOKS: It was apparently concluded that the study of possible hazards to spacecraft penetrating the asteroid belt was of higher priority than studies of asteroids per se. Also, the close encounters I described require maneuvering capability beyond the existing Pioneer F and G design. A capability of 0.5 to 0.6 km/s is possible without major redesign of the spacecraft. A capability of 0.9 km/s may be possible with the same type of propulsion system (hydrazine), but a major redesign of the spacecraft may be necessary. Such a capability would be required for a Jupiter orbiter, as I pointed out in the paper.

FORWARD: Is it possible to send multiple flyby missions into "clumps" of asteroids or to match the orbits of, for example, the Trojan asteroids?

BROOKS: Matching orbits requires much more propulsive capability than flyby missions, and therefore such a maneuver was not considered in this paper. Flying into a group of asteroids would still mean, in general, that only one member of the group could be approached closely. This is because maneuvering from one point to another point close in time, but not on the unperturbed trajectory, requires a large velocity change.