Opportunities for Multiple Asteroid Flybys in the 1970's and 1980's

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For launch opportunities in the late 1970's and early 1980's, it is possible to find many multiple asteriod flyby (MAF) mission opportunities. Flybys of three or four numbered asteroids are possible with a spacecraft ΔV capability of less than 1 km/sec. Many three-target flybys require less than 600 m/sec. The major technical problems associated with MAF missions are due to the small size and poorly known orbits of most asteroids. These factors make acquisition, guidance, and science measurements difficult for very small asteroids. However, once these difficulties are resolved, MAF missions will be able to provide a significant increase in knowledge of basic properties of asteroids, thereby laying the groundwork for more sophisticated rendezvous and sample return missions.

Introduction

THE feasibility of flying close to several asteroids with a single, small chemically propelled spacecraft was first demonstrated by Brooks and Hampshire in 1971.[1] Previously, several authors have mentioned the general desirability of such missions in conjunction with mission analysis studies for solar electrically propelled spacecraft,[2-4] and more specific proposals have also been made for asteroid observations to be included in Mars missions[5] and flights to the outer planets.[6]

The physical properties of nearly all asteriods—even basic quantities like size, shape, and mass—are unknown. Nevertheless, it is expected that one of the virtues of asteriods will be their structural simplicity relative to the major planets. There exists the probability of discovering records of solar system activity preserved intact on and in bodies whose surfaces have not been eroded by a turbulent atmosphere, or littered by the debris resulting from a large gravitational field, and whose interiors have long ago reached thermal equilibrium. It seems likely that accretion and fragmentation processes are at work simultaneously in the asteroid belt offering in the first instance the chance to observe formation processes in a way otherwise impossible to achieve, and in the second instance, the opportunity to observe in fragmented asteroids the now-exposed interiors of bodies formed long ago.

Multiple asteriod flyby missions provide the ideal means for obtaining needed preliminary data about asteriods, as well as for generating scientific interest in these bodies. The paucity of basic physical data for asteroids, coupled with their predicted relative structural simplicity, means that small, unsophisticated spacecraft can add substantially to the body of knowledge about asteroids by making simple measurements—size, shape, mass and so forth—which can be unambiguously interpreted. Such observations not only pave the way for future space missions, but are of great value in the interpretation of ground-based observations.

In this paper, trajectory characteristics are described for several representative multiple flyby missions, many of which are constrained to include a flyby of Ceres, the largest asteroid.

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Science Objectives of Multiple Asteroid Flyby Missions

Multiple asteroid flyby missions can and should perform a dual function: first, they provide useful information which can be a start toward understanding the asteroid population as a whole and, second, they serve as precursor missions for future more sophisticated missions to comets and asteroids. Thus, the multiple asteroid flyby concept relates to future small-body missions much as the Poineer F and G program of Jupiter flybys rleates to Jupiter orbiters and other outer planet missions.

Some scientific objectives of the flyby missions described in Ref. 1 have been enumerated by Bratenahl[7] and discussed more generally in many of the contributions to the 12th Colloquim of the International Astronomical Union.[8] These objectives include: 1) asteroid size, shape, and albedo, 2) asteroid mass, 3) distribution of asteroid surface reflectance as a function of lighting angle and estimate of surface composition by reflectance spectroscopy, 4) infrared asteroid surface temperature, and 5) data concerning asteroid belt particle densities to submicrometeoroid sizes and investigation of particle jet streams. Achievement of many of these goals depends on experiments which are optical in nature and, in fact, the optical system of any spacecraft designed for multiple asteroid flybys will emerge as the most challenging technical problem to be faced in systems design for the missions described in this paper.

Mission Analysis

Multiple asteroid flyby (MAF) missions are conceived as ballistic flights through the asteroid belt, in or near the ecliptic plane, during which a small and relatively simple spacecraft performs low-energy orbital maneuvers such that it flies close enough to at least three preselected asteroids to allow measurement of basic physical properties of the target object. The chances for achieving close flybys of the numbered asteroids without maneuvering a spacecraft are negligible; Ref. 1 shows that the chance of encountering even one of the 1748 numbered asteroids[9] at a distance of no more than 15,000 km is less than 1 in 10^5 for a typical trajectory.

Trajectory Analysis

The basic logic for studying MAF opportunities is contained in a computer program which compares Cartesian position coordinates of a spacecraft with the positions, at the same time, of the 1748 numbered asteroids. Target positions are computed by using the osculating elements in Ref. 9 as Kepler elements and advancing the asteroids along unperturbed ellipses to the desired time. The positions so generated are considered exact—the errors which can accumulate due to planetary perturbations are not considered significant for the purpose of this study. The spacecraft trajectory may take any of three forms: 1) an ellipse having its perihelion at Earth on the launch date and its aphelion at a specified heliocentric radius in the ecliptic; 2) any externally generated trajectory specified in heliocentric ecliptic coordinates at time intervals of no more than a few days; 3) an internally generated trajectory which is launched on a particular date and is constrained to intercept a specified point at a specified time. As the positions of spacecraft and asteroids are computed, their relative separations are compared against a preselected search radius, and all asteroids which pass within the search radius are counted as possible targets for that particular mission. Experience has shown that search radii between 0.1 a.u. and 0.2 a.u. will produce a sufficiently large number of possible encounter sequences to yield several acceptable missions for any trajectory through the asteroid belt.

Once possible targets have been identified for a nominal spacecraft trajectory, the maneuvering ΔV for various flyby sequences are computed. This quantity does not include allotments for terminal maneuvering or attitude control, and impulsive velocity changes are assumed. The launch date is fixed, and an adaptive creeping technique is used with an algorithm for solving Lambert's problem to adjust the encounter dates in such a way as to minimize the ΔV required to complete a desired flyby sequence. The asteroids are assumed to be massless points which are intercepted exactly by the spacecraft and the dates of closest approach along the nominal trajectory are used as starting points for the optimization procedure. The launch date is then varied to isolate the local minima for both the onboard spacecraft ΔV and the hyperbolic velocity (V_∞) required to launch the spacecraft. (The minima for these two quantities generally occur for different launch dates.) Figure 1 illustrates how the major maneuvers are accomplished for a three-asteroid sequence. The solid line indicates the nominal elliptical trajectory along which the search for targets is made. The dotted line shows the final path of the spacecraft after an encounter sequence has been selected; the launch conditions are adjusted slightly to intercept the first asteroid, and the spacecraft performs two ΔV maneuvers to alter its orbit and intercept the second and third targets.

Target Selection

A basic assumption of the MAF concept is that appropriate missions may be found at any time and that for a simple reconnaissance-type mission, there is not much reason to favor one asteroid over another. That randomness of launch date and target selection are possible is evident in Ref. 1 and in that part of this study which deals with a randomly selected launch data in 1981; but for several of the present examples, a flyby of Ceres was imposed as a condition on the trajectories to be launched in 1979. Such a restriction is more for the purpose of bounding the study in some way than it is for the purpose of favoring Ceres over other targets; for the year in which minimum-energy transfers to Ceres were used as nominal trajectories, many other missions not involving Ceres could just as well have been examined. However, there is an argument to be made favoring inclusion of Ceres in an MAF sequence. As the largest minor planet, Ceres contains a sizable fraction of the total mass of the asteroid belt, and is so large (estimated diameter of 770 km) as to be highly atypical of asteroids. It is more likely to be lunarlike than it is to be a fragment of primordial material. (The next largest asteroid, Vesta, is also atypical, having a high albedo which indicates a surface quite different from those few other asteroids for which albedo has been measured.) Thus, scientists who favor an eventual sample return from a small asteroid which passes close to the Earth would be expected to express little interest in devoting such a mission to any large minor planet in the asteroid belt. As a result, potentially unique bodies like Ceres and Vesta will probably not be studied in the foreseeable future except on flyby missions.

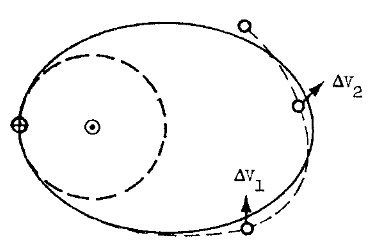

Fig. 1 Multiple asteriod flyby mission schematic.

One additional argument favoring inclusion of large asteroids in MAF sequences is the obvious fact that measurements of any kind should be made easier. However, other than the partiality shown to Ceres in this study, no other attempt has been made to bias the selection of targets toward larger asteroids. In a few cases, where many possibilities for encounter sequences were found to exist, targets have been excluded when others were available at about the same date with significantly lower velocities relative to the spacecraft. As far as other criteria for target selection are concerned, it is fruitless to try to define and select "typical" minor planets on the basis of a sample as unrepresentative of the total asteroid population as the numbered asteroids; there are certainly many tens of thousands of minor planets too faint to be seen from Earth, in addition to the estimated 30,000 to 50,000 which could be observed and whose orbits could be accurately determined if there were sufficient justification for doing so.[10] Of course, such a limited knowledge of the expected body density in the asteroid belt and ignorance of the properties of a "typical" asteroid are just two of the unknowns which make MAF missions desirable.

Trajectory Properties of MAF Encounter Sequences

Basic trajectory properties for the multiple encounter sequences selected for presentation in this study are summarized in Tables 1 and 2. The criterion for inclusion in the tables is that each encounter must require no more than 1 km/sec of spacecraft ΔV, defined and optimized as described previously. Table 1 contains encounter sequences for missions which include Ceres flybys, launched in 1979. Table 2 contains sequences for an arbitrarily chosen launch date in 1981. In each table, the first column gives the sequence, with the asteroid numbers corresponding to those in Ref. 9. In the following columns, Julian date of launch, spacecraft (S/C) ΔV and hyperbolic excess velocity V_∞ are tabulated from a search for minimum ΔV.

The encounter sequences tabulated in Tables 1 and 2 have been arrived at by a systematic search of all possible encounters among asteroids which pass within 0.2 a.u. of the selected

Table 1 Multiple encounter sequences on a flyby of Ceres[a]

Encounter sequence	Julian date of launch (244XXXX)	$S/C\ \Delta V$ (km/sec)	V_∞ (km/sec)
422-1-993	4050	0.938	6.44
422-1-1153	4050	0.638	6.35
1473-1-1153	4060	0.116	7.01
1473-1-1382	4055	0.513	6.59
1473-1-443	4025	0.566	6.60

[a] To be launched in mid 1979.

Table 2 Multiple encounter sequences on a randomly chosen trajectory launched in mid 1981

Encounter sequence	Julian date of launch (244XXXX)	$S/C\ \Delta V$ (km/sec)	V_∞ (km/sec)
1515-1674- 561	4790	0.448	6.94
1515- 870-1720	4790	0.075	6.96
1515- 561-1720	4790	0.399	6.96
1515-1674-1720	4790	0.515	6.93
149- 870- 561	4780	0.707	7.67
149- 870-1720	4780	0.307	7.66
1674- 561-1720[a]	4800	0.455	6.85
1515-1674- 561-1720	4795	0.693	6.87
1515-1674- 870-1720	4795	0.925	6.76

[a] $S/C\ \Delta V$ can be lowered by increasing V_∞.

nominal spacecraft trajectory. It is probable that accepting a larger search radius would result in additional sequences, as it is not possible to determine a priori the ΔV requirements for given targets strictly on the basis of their distance of closest approach to the spacecraft on its nominal trajectory, but the list is not intended to be exhaustive for each launch opportunity. In fact, as the search for local ΔV minima is made by varying the nominal launch date, additional sequences become possible, although flights which are constrained to include a particular target are limited by a rapidly increasing launch energy as the launch is moved away from the best date for that target. The unconstrained flybys provide what amounts to an infinitely wide launch window, with the most advantageous encounter sequences changing every few days. Complete analysis of a given range of available launch dates for multiple flybys is not justified in a preliminary feasibility study, due to the large amounts of computer time required.

A detailed description of the variations in ΔV and V_∞ for the 1979 Ceres mission is contained in Figs. 2 and 3. In Fig. 2, the ΔV's for the five three-body sequences from Table 1 are shown as a function of launch date, optimized for each date. Over the same range of launch dates the V_∞'s for the same five missions vary as shown in Fig. 3. The minimum values of V_∞ lie between 5.88 and 6.23 km/sec. Comparisons of Figs. 2 and 3 and Table 1 show clearly that there are possibilities for trading off spacecraft ΔV against V_∞.

It is not surprising to learn from an examination of MAF opportunities that missions requiring low spacecraft ΔV generally correspond to trajectories for which the targets are spread far apart in time. The heliocentric orbital periods for spacecraft trajectories having aphelia in the asteroid belt range from 605 days at 1.8 a.u. to 1316 days at 3.7 a.u., so the amount of time available between targets is on the order of hundreds of days. For example, the 1979 mission 1473-1-1153 would be launched on J. D. 2444060 (July 1979)

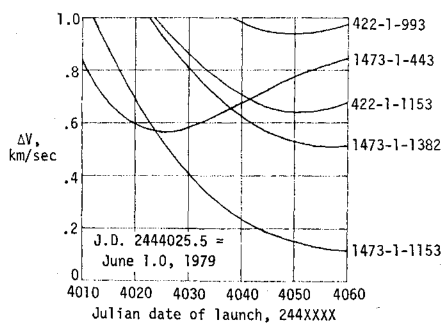

Fig. 2 Spacecraft ΔV requirements for three-target encounters on 1979 Ceres flyby missions.

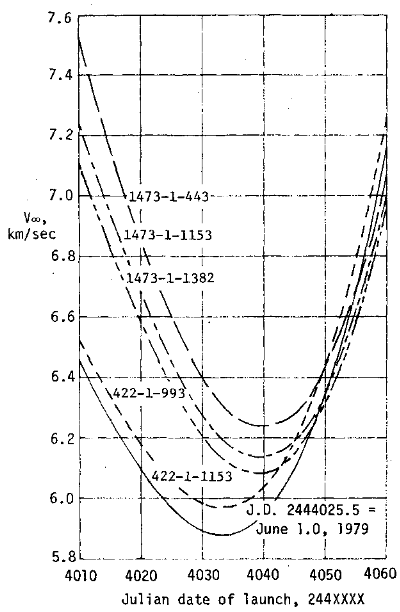

Fig. 3 Launch energy requirements for three-target encounters on 1979 Ceres flyby missions.

and encounters 1473, 1 (Ceres), and 1153 at 2444257 (Jan. 1980), 2444477 (Aug. 1980), and 2444634 (Jan. 1981), respectively. The total mission time from launch to last encounter is 574 days.

Geometry During Asteroid Flybys

There are several properties of MAF trajectories in the vicinity of the target asteroids which are essential to an understanding of the feasibility of such missions—especially the feasibility of visually acquiring an asteroid prior to a close encounter. These quantities, referenced to the observation point onboard the spacecraft are: relative flyby velocity, sun lighting angle at target acquisition, time from closest approach, cone and clock angles, and Earth-spacecraft communication distance.

The relative velocity during the flybys ranges from about 5 to 15 km/sec for the sequences in this study. The first column of Table 3 gives the relative velocities for all the encounters listed earlier in Tables 1 and 2. For main-belt asteroids and spacecraft constrained to remain in the asteroid

Table 3 Relative velocity, magnitude, and estimated diameter for asteroids involved in encounter sequences listed in Tables 1 and 2

#	V_{rel} (km/sec)	g	Diameter (km)
1979 Ceres			
1	6.2	4.0	770
422	8.1	12.0	15
443	10.1	11.5	19
993	5.4	13.3	8
1153	6.7	13.3	8
1473	8.0	13.5	7
1981			
149	11.1	12.0	15
561	10.5	11.9	16
870	5.1	12.9	10
1515	11.4	13.8	7
1674	8.3	11.9	16
1720	12.3	14.3	5

belt, the lighting angle is smallest for encounters before aphelion; it passes through 90° at aphelion and can give very poor lighting conditions for encounters much past spacecraft aphelion. For these missions cone and clock angles can vary over a large range of values and this fact will be important to analysis of any spacecraft design. As the outer edge of the asteroid belt is about 3.7 a.u., Earth-spacecraft communication distance can be as large as 4.7 a.u.

Systems Considerations

The preceding sections have examined several specific flyby opportunities. The examples given must be considered as representative and it is fair to conclude from the data presented that, when not restricted to a greater extent than has been done in this study, MAF missions are available on a continuous basis. The trajectory characteristics of such missions—launch energy, spacecraft ΔV requirements, launch constraints, flight times, encounter conditions—are reproducible in a general way for any launch date.

The values of V_∞ needed for the flybys tabulated in Tables 1 and 2 lie between 6 and 8 km/sec and suggest launching the MAF missions with an Atlas/Centaur/3rd stage as used with Pioneer F&G. The entire asteroid belt is accessible with this launch vehicle and a spacecraft of up to at least 500 kg.

A cautionary remark is in order regarding the spacecraft ΔV's listed in Tables 1 and 2. Although the encounter sequences have been locally optimized, the exact values of ΔV are quite sensitive in some cases to the time of encounter and the target positions. A detailed analysis of any particular flyby sequence could result in higher ΔV's once orbits were accurately computed and allowances are made for insuring reasonable arrival windows. Of course, some of the ΔV's could just as well go down, and there is no reason to suspect that any of the numbers given in Tables 1 and 2 are unrepresentative of what might be required on actual missions.

The small size and poorly known ephemerides for asteroids and the poor lighting conditions at which they may be encountered on flyby trajectories pose the major problems in the design of detection and measurement instrumentation for MAF missions. Acquisition of the target asteroid as long as possible before the actual encounter is a necessity for MAF missions. Early acquisition minimizes terminal guidance propulsion requirements and maximizes the time available for Earth-spacecraft communication ($\sim$1 hr round trip) prior to the encounter. Discussion of the behavior of the apparent magnitude of an asteroid as a function of size and lighting angle can be found in the work of Gehrels.[11–12] Once the target has been acquired and terminal guidance maneuvers have been accomplished the requirements for optical measurements become important. For representative system performance, the closest approach needed for high-quality pictures of an asteroid's surface may be so close that the instrument pointing system can no longer track the moving target.[13] However, it is not possible presently to define the limits of this problem.

Determination of the mass of a small body is a goal which has the highest scientific priority, and an accuracy of even 10–20% would be acceptable as the present uncertainty covers factors of 2 or more. The two available methods—spacecraft tracking and gravity gradiometers—both have possibilities and limitations which require further study. Discussions of both methods applied to this problem may be found in papers by Anderson and Forward.[14–16]

It is not now known how accurately the position of an asteroid must be predicted to allow terminal guidance to within a few hundred kilometers of the asteroid surface. The accuracy requirement depends largely on the performance of a target acquisition sensor which is not yet defined. Marsden[17] has stated that positions of almost all numbered asteroids can be predicted within a few thousand kilometers, but additional work needs to be done, especially for very small asteroids which cannot be detected far in advance of the flyby encounter.

Conclusions

Based on current attitudes toward planetary exploration, multiple asteroid flyby missions should receive widespread scientific support both on their own merits and as precursors to more sophisticated small-body missions. The goal of MAF missions is to determine basic physical properties of several minor planets. Flybys of three or four asteroids on a single mission to the asteroid belt are possible with a spacecraft ΔV capability of a few hundred meters per second. Such missions are available on a continuous basis, with no significant launch date restrictions. The main technical and science measurement problems result from the small size of asteroids and the conditions under which they are encountered, making some aspects of the mission questionable under the worst conditions. Inclusion of large asteroids on flyby missions guarantee the feasibility of measuring basic physical properties. Detailed studies of a particular mission are required to determine whether, or the extent to which, target selections will have to be restricted to satisfy measurement constraints. However, once these constraints are satisfied, either by target restriction or technological sophistication, MAF missions provide a relatively inexpensive way to begin understanding the properties of the asteroid belt.

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Design of Graphite Nosetips for Ballistic Re-Entry

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Analyses are given for re-entry shape change and indepth thermal/structural response of contemporary low-recession graphite nosetips. Both blunt plug configurations and sharp and blunt shell designs are treated from the principal viewpoint of surviving thermally induced tensile strains. Parametric calculations demonstrate the magnitude and variation in these re-entry thermal strains and their sensitivity to initial re-entry conditions and to various thermal and mechanical modeling elements in the design analysis sequence. In addition to thermal strain, a number of other design problems peculiar to graphite nosetips are discussed in their relationship to over-all re-entry vehicle thermal/structural capability.

Nomenclature

B_w' = mass-transfer parameter
c = specific heat, Btu/lb-°F
d = nosetip overhang radius, ft
E = elastic modulus, lb/in^2.
g = acceleration of gravity, ft/sec^2
H = enthalpy, Btu/lb
h = heat-transfer coefficient, lb/sec-ft^2
k = thermal conductivity, Btu/sec-ft-°F
M = Mach number
m = mass, lb
p = pressure, atm
Q = total convective heat load, Btu/ft^2
q = instantaneous heat rate, Btu/sec-ft^2
$\bar{q}$ = dynamic pressure, atm
R = radius of curvature, ft
Re = Reynolds number
R_N = nosetip radius, ft
r = radial coordinate (from centerline)
$\dot{s}$ = surface recession rate, fps
s = total stagnation-point recession, ft
t = temperature, °F
V_E = re-entry velocity, fps
x = axial coordinate (from stagnation point)
y = normal distance from original heatshield surface, ft
z = altitude, ft
β = thermal-expansion coefficient, in/in.-°F
$\bar{\beta}$ = ballistic coefficient, lb/ft^2
Γ = permeability, ft^2
γ_E = re-entry angle, deg
δ = nosetip overhang length, ft; deflection, ft
ε = thermal strain, %
ζ = mechanical erosion amplification factor $= \dot{s}_{\text{total}}\ \dot{s}_{\text{chem}}$
θ = time, sec
λ = re-entry parameter $= (V_E{}^2/g)(\bar{\beta}/\rho_0 R_N{}^3 \sin\gamma_E)^{1/2} x10^{-10}$
ν = Poisson ratio
ρ = air density, lb/ft^3

Subscripts

c = cavity, critical (onset) value
chem = chemical
E = re-entry
e = boundary-layer edge value
hoop = hoop (circumferential) direction
N = nosetip
r = radial
$r - x$ = pitch plane
sp = stagnation point
t = tensile
x = axial
w = wall (surface or internal) value, wedge
0 = sea level
θ = momentum thickness

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Index categories: Thermal Modeling and Experimental Thermal Simulation; Optimal Structural Design.

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Introduction

AN increasing number of unclassified technology papers have appeared in recent years on the subject of ballistic-re-entry nosetips. Some have considered reinforced plastics[1] and others reinforced carbon nosetip materials.[2,3] Papers dealing with graphite nosetips have concentrated primarily on shape change and thermal response[4–6] and with ground testing of materials and subscale nosetip configurations.[7–9]