Engineering Notes

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Mission Strategy for Combined Comet-Asteroid Flybys

DAVID R. BROOKS*
NASA Langley Research Center, Hampton, Va.

IT is well known that there exist many possibilities for ballistic fast flybys of short-period comets in the late 1970's and early 1980's. These opportunities can often be identified merely by examination of a list of comet orbit elements.[1] The flyby trajectories can be constrained in a variety of ways, and one possibility is to select trajectories which pass through the asteroid belt in such a way as to allow close approaches to one or more asteroids. Examination of the resulting multiple comet-asteroid flyby opportunities can then proceed using rationale and computational techniques developed previously for multiple asteroid flybys.[2,3]

A list of cometary targets is given in Table 1, along with some trajectory data for fast ballistic flybys which are constrained to pass through the asteroid belt and encounter the target comet at the node nearest perihelion. The launch energy requirements for small ballistic spacecraft which reach into the asteroid belt can easily be met with Atlas-class launch vehicles. All the trip times over 500 days indicate comet intercepts after aphelion of the spacecraft trajectory. Some additional details of the encounter include the intercept radius R_{node}, relative velocity V_{rel}, communication distance to earth R_{comm}, time from comet node to comet perihelion T_p (a negative number means that the intercept is after comet perihelion), and comet-sun distance at comet perihelion R_p.

Just on the basis of relative velocity during the encounter, one would rate the Forbes '77 and '78 missions as the most favorable, followed by Reinmuth 2 '78, van Biesbroeck '78, Arend '81, and Schwassmann-Wachmann 2 '79. It turns out that the Forbes missions are highly desirable, and the '77 launch will be used to illustrate the type of asteroid encounters to be expected on fast ballistic comet flybys.

Pertinent orbital data for Forbes have been provided by or computed from information supplied by Dr. Brian Marsden.[7] The first recorded apparition of the periodic comet Forbes was in August 1929. It has a period of about 6.4 years. While it has not been observed on every return since 1929, it will be observable in early 1974, prior to its perihelion passage in May 1974 and again in early 1980. The perihelion passage in September 1980 follows a nodal crossing in April 1980 (J.D. 2444348.87) which is the nominal target point for the proposed flyby. The orbit elements of Forbes in early 1980 are as follows:

Table 2 Orbit elements for comet Forbes

Epoch	Jan. 2.0 1980	i 4.666°
M	317.963°	e 0.565
ω	262.559°	μ 566.113 sec/day
Ω	23.001°	a 3.994 AU

Table 1 Selected comet flyby opportunities in the late 1970's and early 1980's

Comet	Launch date, 244XXXX (mo/yr)	V_∞, km/sec	R_a,[a] AU	J.D. of node, 244XXXX	Trip time, days	R_{node}, AU	V_{rel}, km/sec	R_{comm}, AU	T_p,[b] days after node	R_p,[b] AU
Forbes	3370(8/77)	7.25	3.33	4348.87	979	2.16	3.81	1.16	151	1.48
van Biesbroeck	3560(2/78)	6.13	2.69	3992.86	433	2.69	9.85	3.13	−147	2.40
Forbes	3760(9/78)	5.79	2.46	4348.87	589	2.16	6.74	1.16	151	1.48
Reinmuth 2	3850(12/78)	6.06	2.65	4522.59	673	2.14	7.44	2.23	111	1.95
Borrelly	3930(2/79)	5.62	2.43	4662.20	732	1.32	20.38	1.57	−7	1.32
S-W2[c]	4040(6/79)	6.06	2.57	4685.41	645	2.14	10.43	1.78	−5	2.14
Reinmuth 2	4300(3/80)	6.00	2.62	4522.59	223	2.14	15.22	2.23	111	1.95
Kearns-Kwee	4430(7/80)	6.46	2.78	5082.58	653	2.50	13.86	2.48	−143	2.22
S-W2[c]	4500(9/80)	8.03	4.06	4685.41	185	2.14	13.92	1.78	−5	2.14
Neujmin 3	4610(1/81)	6.51	2.94	5394.59	785	2.20	16.66	3.18	−85	2.06
Arend	4630(1/81)	6.22	2.77	5369.61	740	2.04	10.08	2.92	108	1.86

[a] Spacecraft orbit.
[b] Comet orbit.
[c] Schwassmann-Wachmann 2.

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* Aerospace Engineer, Mission Analysis Section, Analysis and Advanced Concepts Branch, Space Applications and Technology Division. Member AIAA.

Marsden has estimated that the total absolute magnitude will be about 9.0 and that the nuclear absolute magnitude is about 15.5.[7] There are still nongravitational forces evident in Forbes' motion, but they are predictable enough for a reliable ephemeris in 1980 if good observations are made during 1974. During the proposed mission, Forbes should be observable starting in early March of 1980 and it should be noted that this is not far in advance of the desired encounter during the last half of April. During the encounter the earth is a little more than 1AU from Forbes, near the minimum.

Following previously outlined procedures for mission analysis,[2,3] a nominal earth-Forbes flyby trajectory has been generated which approaches Forbes just at its descending node to eliminate out-of-the-ecliptic maneuvers. For a fixed arrival date of J.D. 2444348.87 (April 19, 1980), the minimum-energy launch date is about J.D. 2443370.5 (August 15, 1977) at conditions allowing a due east launch. The hyperbolic excess velocity is 7.245 km/sec; the nominal trajectory has $a = 2.169$ AU and $e = 0.533$. The spacecraft leaves earth very near perihelion of the trajectory and encounters Forbes at a true anomaly of 238°, 978 days later.

A spacecraft following the above trajectory comes within 0.2 AU of 41 numbered asteroids, 16 of which pass within 0.1 AU, but none of which pass closer than 5×10^6 km. The first one has its closest approach around J.D. 2443545.5 (February 5, 1978) and the last about 2444324.5 (March 25, 1980), less than a month before the Forbes encounter. It is from among this list of 41 possible targets that the final encounter sequences will be sought. Nine of the asteroids passing within 0.2 AU of the spacecraft have an absolute magnitude of 10 or less, giving them diameters > 50 km. It would be desirable to include at least one of the large asteroids on the proposed missions. The shape of the nominal trajectory described above suggests sequences in which two asteroids are encountered first, and then Forbes.

Sequences of the type asteroid-asteroid-Forbes have been searched as described previously[2,3] to find those missions with the lowest spacecraft propulsion for reducing the naturally occurring miss distances to nominally zero (assuming the asteroid location is known precisely). The requirements so computed do not account for the propellant required to maneuver the spacecraft after the target has been visually acquired, to correct for inexact prediction of the target ephemeris. There are dozens of possible two asteroid-Forbes sequences, and no attempt will be made to list all of them. The foremost constraint on the flyby trajectories is the spacecraft propulsion requirement, which is ideally restricted to a few hundred mps and in no case more than 1 km/sec. There is an additional constraint on the Forbes mission which may make some of the otherwise suitable sequences unacceptable: the spacecraft propellant requirement is minimized by allowing the arrival dates at the targets to vary freely, while the launch date remains fixed. In some cases, this freedom means that the arrival at Forbes will be substantially earlier or later than specified in the nominal trajectory, with the spacecraft providing propulsion for the resulting small out of-the-ecliptic maneuvers. A date much earlier than that suggested by the nominal trajectory will mean that no earth observation of Forbes will be possible prior to the encounter. This is not too serious from the scientific point of view, considering the observational objectives of fast flybys, but an orbit determination for Forbes may not be done in time to allow a midcourse correction to be made in the spacecraft trajectory prior to visual acquisition.

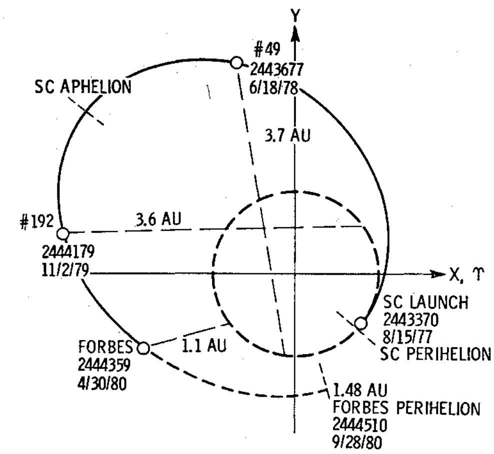

Fig. 1 Schematic representation of trajectory for flyby sequence 49-192-Forbes.

In this Note, attention will be focused on a particularly interesting set of missions involving some large asteroids. Asteroid No. 49 (Pales—about 100 km in diam) can be combined with several other sizable objects to yield flyby sequences; a list is given in Table 3. Table 3 includes, for each flyby sequence, the arrival times at each target to achieve minimum spacecraft propulsion, the ΔV increments required for retargeting after passing by the first and second targets, the total ΔV, the hyperbolic excess velocity required for launch, the lighting angles (Θ is the spacecraft-target-sun angle a day or so prior to closest approach), relative velocities, communication distances for each target, and the heliocentric distance to Forbes at encounter. Orbital data for the target asteroids have been supplied by the Minor Planet Center of the University of Cincinnati[8]; additional details may be found in Refs. 4 and 5.

A projection into the ecliptic of the spacecraft orbit for the mission 49-192-Forbes is illustrated in Fig. 1. It is clear from this figure that the low relative velocity at Forbes occurring for all the missions in Table 3 is due to the fortuitous alignment of Forbes' perihelion, as the spacecraft orbit is nearly tangential to Forbes' orbit during the encounter. The fact that Forbes has an inclination of only 4.67° also helps to keep the relative velocity down, as the spacecraft always moves nearly in the plane of the ecliptic.

An examination of the data presented in Table 3 shows that the general encounter characteristics of these missions can be summarized as follows: the first target, asteroid No. 49, is approached at about 6 km/sec with a lighting angle around 50°. The second

Table 3 Trajectory Characteristics of Multiple Flyby Missions Including the Comet Forbes—Launch Aug. 15, 1977

	$T_{1,2,3}$, 244XXXX	$\Delta V_{1,2}$, mps	ΔV_T, mps	V_∞, km/sec	$\theta_{1,2,3}$ deg	$V_{\mathrm{rel}\,1,2,3}$, km/sec	$R_{\mathrm{comm}\,1,2,3}$, AU	$R_{\oplus\text{-Forbes}}$, AU
49-192-Forbes	3655, 4185, 4343	204, 852	1056	7.13	44, 159, 69	6.76, 8.51, 3.75	3.50, 3.58, 1.20	2.20
300	3670, 3974, 4380	348, 578	926	7.01	51, 102, 68	6.28, 5.00, 4.16	3.61, 2.78, 1.13	1.96
303	3659, 4112, 4325	177, 090	267	7.09	45, 134, 69	6.62, 7.16, 3.89	3.53, 4.15, 1.34	2.31
327	3659, 4202, 4330	144, 234	378	7.09	45, 139, 70	6.62, 7.17, 3.87	3.53, 3.38, 1.30	2.29
592	3674, 4135, 4391	476, 187	663	6.98	51, 143, 99	6.17, 8.35, 4.52	3.64, 4.06, 1.16	1.90
609	3657, 4118, 4332	101, 484	585	7.11	45, 127, 68	6.69, 6.22, 3.82	3.52, 4.13, 1.28	2.27

target is approached at between 5 and 8 km/sec, with a lighting angle between 90° and 160°; there is a positive correlation between approach velocity and lighting angle. Forbes is encountered at about 4 km/sec, with a lighting angle less than 100°, depending on the date of encounter (the viewing angle during target acquisition is critical for comets only when the spacecraft is looking toward the sun). The communication distance for the second target can be greater than 4 AU, but this is a penalty which must be expected for any mission which seeks to sample targets near the outer edge of the asteroid belt.

Inclusion of a large asteroid like No. 49 at the start of the flyby sequence has important advantages. Acquisition at a large distance is assured, thereby minimizing terminal maneuvering requirements (No. 49 appears as a fifth magnitude object at a distance of about 6×10^6 km for the trajectories presented here). The crucial problem of mass determination is not difficult for a 100-km-diam object—Ref. 6 shows that for such a target a miss distance of 10^4 km will allow a mass determination to an accuracy of better than 10% with conventional *S*-band Doppler tracking. Measurements requiring only the total integrated light from the target—infrared temperature, polarimetry, photometry—can be done from a greater distance with a lower apparent motion for which to compensate.

Conceptually, it has been assumed that a modified Pioneer *F* and *G* spacecraft is the favored vehicle for performing multiple flyby missions. Propulsion requirements for some of the missions listed in Table 3 leave an ample performance margin for modified Pioneer vehicles. After the asteroid encounters are performed and the main retargeting maneuver is performed to intercept Forbes, any extra propellant beyond the terminal guidance allotment for Forbes could profitably be used to delay the arrival at Forbes, giving an encounter closer to perihelion and allowing more time for earth observation of Forbes prior to the encounter.

TRW Systems Group, in considering the applicability of modified Pioneer spacecraft to multiple asteroid flyby missions, has concluded that terminal maneuvering initiated 10^6 km from a target 10^4 km from its predicted position and moving at a 6-km/sec relative velocity can be performed with two or three separate maneuvers, the last being no later than 10 h from closest approach, for a total of 50 mps.[9] Halving the encounter distance approximately doubles the propulsion needed, as expected. For the missions presented here, the second target consumes the most propellant, as the lighting conditions are worse than for the other two targets. An allowance of 200 mps should be ample to cover the terminal maneuvering requirements for all three targets, regardless of which mission is selected from the set listed in Table 3.

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Advanced Applications of the Space Shuttle

James E. Blahnik*
Science Applications, Inc., Marietta, Ga.

AND

Donald R. Davis†
Planetary Science Institute, Tucson, Ariz.

I. Introduction

THE projected Space Transportation System (STS) traffic models for the initial era of the Space Shuttle (1980–1990) display a large amount of traffic to and from synchronous orbit. Projected traffic models require the use of either expendable-type stages or a reusable Space Tug with the Space Shuttle to perform the Earth orbit high energy missions. Neither of these concepts can carry the largest future payloads to synchronous orbit on a single flight. In addition, no provision is made for man (should he be required) on these missions. With the large number and size of payloads projected for synchronous missions in the coming decades, it appears that a manned system which can deliver several payloads on a single mission, and thus reduce the total number of missions required, may be desirable. Such a system could be the Space Shuttle Orbiter to perform not only Earth-synchronous missions but also future manned lunar exploration.

The guiding philosophy for advanced applications of the Space Shuttle is to minimize any significant modifications and, hence, to minimize costs. The basic assumptions used in this Note are: a) The basic Shuttle Orbiter design will be utilized, i.e., mainframe, engine, tanks, b) The vehicle configuration and aerodynamic data are similar to Phase B concepts. c) The Shuttle Orbiter can be refueled in Earth orbit. d) The nominal 7-day design sortie can be extended up to 30 days by adding consumables which are charged against the payload.

The Space Shuttle is designed for a nominal 7-day mission in the near-Earth environment, terminating with a re-entry velocity of approximately 7600 m/sec; advanced applications will require missions approaching 30 days duration and re-entry speeds up to 11,000 m/sec.

For the synchronous orbit missions, requirements may be

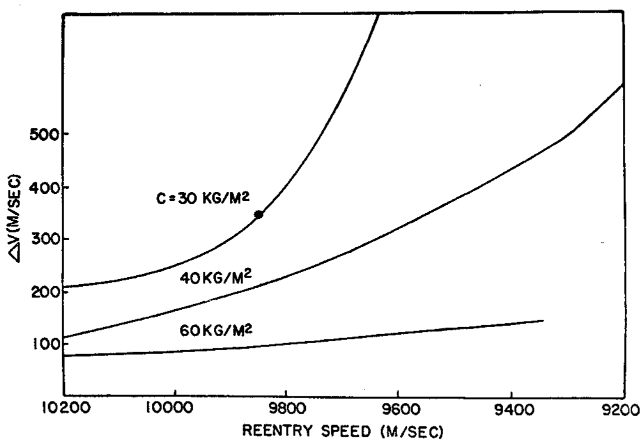

Fig. 1 Speed loss for skipping re-entry trajectory.

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* Senior Engineer.
† Staff Scientist.