Accessibility of Near-Earth Asteroids

C.O. Lau*
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California
and
N.D. Hulkower†
TRW Inc., Redondo Beach, California

Missions to near-Earth asteroids are of interest to both scientists and prospectors in search of extraterrestrial materials. The primary consideration in selecting the object to explore is accessibility. The measure of accessibility is taken to be the global minimum total ΔV for a two-impulse transfer or less than 360 deg from standard shuttle orbit to rendezvous with the asteroid. A ranking by accessibility of all known near-Earth asteroids is presented. In addition, actual mission opportunities with launch dates between 1990 and 2010 for the most accessible are listed and compared with the optimal rendezvous. Actual sample return opportunities are investigated for the very best candidates.

Introduction

BALLISTIC missions to the near-Earth asteroids have received serious study in the past few years. These minor planets have attracted the interest of the scientific community[1,2] and of those searching for sources of extraterrestrial materials near the Earth.[3-6] In addition, any planning for a mission to redirect an object on a collision course with Earth would benefit from an advance visit to a similar body.[7] In this paper, we complete and update the ranking of near-Earth asteroids by accessibility introduced in Refs. 8 and 9 and demonstrate its usefulness for selecting objects as mission targets. Seventy-three near-Earth asteroids with discovery dates on or before Feb. 6, 1985 and reliable orbital elements are included. Ballistic rendezvous and round trip trajectories for the more accessible objects are presented for launch dates from 1990 to 2010.

In the next section, the near-Earth asteroids included in this study are listed. The following sections give the ranking by accessibility, rendezvous opportunities, and sample return opportunities. The final section contains conclusions.

The Near-Earth Asteroids

Because of the dedicated search by Eleanor Helin[10] and others, the discovery rate of near-Earth asteroids has accelerated. As of Feb. 6, 1985, 82 minor planets with perihelion distances of less than 1.3 a.u. have been found.[11] Eight of these are considered lost, and one is too recently discovered to have reliable orbital elements, Tables 1 and 2 list all these objects, with their orbital elements, epoch, diameter, perihelion distance, and classification based on a taxonomy developed by Gradie and Tedesco.[12] The large percentage of unnumbered near-Earth asteroids, those having only temporary designations giving the year and order of discovery and awaiting confirmation, attests to the outstanding achievement of the last decade. As we shall see in the next section, most of the best targets for asteroid missions are among the unnumbered.

Received Aug. 23, 1985; revision received Aug. 15, 1986.

*Member of Technical Staff, Advanced Projects Group, Mission Design Section. Member AIAA.

†Manager of Independent Cost Assessment, Space and Technology Group. Member AIAA.

Ranking by Accessibility

The primary consideration in selecting the asteroid to explore is its accessibility. One measure of accessibility introduced in Refs. 8 and 9 is the global minimum total ΔV for a two-impulse transfer of less than 360 deg from standard Shuttle orbit to rendezvous with the target body. The total ΔV is defined as the launch ΔV plus the change of velocity at target. A method already exists to calculate the optimal total ΔV on the space of the launch and arrival true anomalies.[8,13] Figures 1 and 2 combine to illustrate this two-part ranking process. In Fig. 1, the entire space of optimum rendezvous trajectories from Earth to a near-Earth asteroid, in this case 1982 XB, is displayed. The contours represent the minimum total ΔV to transfer from a position on Earth's orbit given by the mean anomaly on the abscissa to a position on the target body's orbit given by the mean anomaly on the ordinate. The trajectories are computed using the patched conic method. The minima are found by varying the semilatus rectum for each fixed pair of mean anomalies on the grid. Then a region that contains the smallest total ΔV is identified. The exact value of the global minimum total ΔV, as shown in Fig. 2, is found by using a trajectory optimizer in an ephemeris-free mode that also varies the position on each orbit. The result is the number used to rank a given near-Earth asteroid by accessibility.

Of the 82 near-Earth asterioids found before Feb. 6, 1985, nine were not ranked. Eight of these minor planets, 719 Albert, 1937 UB, 1959 LM, 1983 LC, 1983 TF2, 4788 P-L, 6344 P-L, and 6743 P-L, are lost. The remaining one, 1984 KB, still has uncertain orbital elements. Tables 3 and 4 rank the seventy-three near-Earth asteroids in the order of increasing global minimum total ΔV. The tables also list the corresponding mean anomalies of Earth at launch and asteriod at arrival. The time of flight for this optimal trajectory is also given. The ten most accessible asteroids are the same ones presented in Ref. 9. The order has changed slightly because better-known orbital elements are now available.

In the first step to find the minimum total ΔV, a patched conic or simple two-body orbit is used, and thus two-impulse trajectories are calculated. In the second step, a more sophisticated trajectory optimizer is used that will, if necessary, add impulses one at a time to lower the total ΔV. For nine asteroids, the global minimum total ΔV is lowered by an additional impulse. These asteroids are 1620 Geographos, 1866 Sisyphus, 2101 Adonis, 3200 1983 TB, 1950 DA, 1974 MA, 1979 VA, and 1982 TA. These cases are marked with a double asterisk in the tables, and both the optimal two-impulse and optimal three-impulse trajectories are included.

Table 1 Orbital characteristics

Asteroid	Semi-Major Axis (AU)	Eccentricity	Inclination (deg)	Longitude of Ascending Node (deg)	Argument of Perihelion (deg)	Mean Anomaly (deg)	Epoch (Julian Date)	Diameter (km)	Perihelion Distance (AU)	Classification
433 Eros	1.4582020	0.2230327	10.82824	303.77080	178.53990	58.49535	2446400.5	22.0	1.133	S
719 Albert	2.5839060	0.5403725	10.82100	186.09300	151.94200	10.07300	2451513.5	2.6	1.190	lost
887 Alinda	2.4933240	0.5580673	9.24842	110.24150	349.67460	4.78861	2446400.5	4.0	1.102	S
1036 Ganymed	2.6627800	0.5373324	26.44990	215.65430	131.53120	26.51491	2446400.5	40.0	1.232	S
1221 Amor	1.9206900	0.4342434	11.89188	170.88680	26.17831	49.88175	2446400.5	1.0	1.087	
1566 Icarus	1.0779430	0.8267640	22.89860	87.52101	31.15750	255.95380	2446400.5	1.4	0.187	U
1580 Betulia	2.1967840	0.4894395	52.01751	61.75858	159.16290	339.33150	2446400.5	1.0	1.122	U
1620 Geographos	1.2447080	0.3353554	13.32096	336.73400	276.56260	298.75230	2446400.5	2.0	0.827	S
1627 Ivar	1.8629160	0.3967102	8.44341	132.67450	167.32720	54.19283	2446400.5	6.2	1.124	S
1685 Toro	1.3672530	0.4358167	9.37386	273.78990	126.82060	81.92183	2446400.5	7.6	0.771	S
1862 Apollo	1.4711050	0.5600663	6.35050	35.40279	285.46310	326.36870	2446400.5	1.4	0.647	S
1863 Antinous	2.2598610	0.6064350	18.41739	346.94280	266.92580	13.80810	2446400.5	3.0	0.889	
1864 Daedalus	1.4608470	0.6149266	22.15889	6.16372	325.35030	28.80959	2446400.5	3.2	0.563	SU
1865 Cerberus	1.0801270	0.4669639	16.09119	212.40750	325.06230	99.70782	2446400.5	1.6	0.576	S
1866 Sisyphus	1.8934340	0.5394511	41.14559	63.10684	292.91440	18.10900	2446400.5	7.6	0.872	U
1915 Quetzalcoat	2.5297620	0.5773503	20.49966	162.44550	347.81230	67.72261	2446400.5	0.4	1.069	SU
1916 Boreas	2.2733690	0.4498601	12.84522	340.30030	335.30470	156.12400	2446400.5	3.0	1.251	S
1917 Cuyo	2.1485590	0.5050175	23.98908	187.85640	194.13810	275.73100	2446400.5	3.0	1.063	
1943 Anteros	1.4301850	0.2559101	8.70253	245.78500	338.10390	128.21000	2446400.5	4.0	1.064	S
1951 Lick	1.3904900	0.0617655	39.09599	130.15070	140.39510	88.40548	2446400.5	2.2	1.305	
1980 Tezcatlipoc	1.7094160	0.3652584	26.84659	246.10970	115.22430	254.07010	2446400.5	6.2	1.085	U
1981 Midas	1.7757860	0.6498993	39.84306	356.59100	267.63300	106.19440	2446400.5	1.6	0.622	
2059 Baboquivari	2.6517140	0.5258013	10.99292	200.48520	191.18860	45.40260	2446400.5	3.8	1.257	
2061 Anza	2.2648870	0.5373158	3.73867	207.34690	155.79510	138.60350	2446400.5	2.4	1.048	C
2062 Aten	0.9664967	0.1825122	18.93476	108.05010	147.85570	12.07915	2446400.5	0.8	0.790	S
2063 Bacchus	1.0776740	0.3494189	9.41987	32.69684	55.01366	337.08430	2446400.5	1.2	0.701	
2100 Ra-Shalom	0.8320720	0.4364827	15.76017	170.29350	355.89350	9.29411	2446400.5	1.6	0.469	U
2101 Adonis	1.8746720	0.7639127	1.36211	350.66660	41.58031	177.53870	2446400.5	2.0	0.443	
2102 Tantalus	1.2900140	0.2984692	64.01204	93.72465	61.64286	246.15020	2446400.5	2.0	0.905	
2135 Aristaeus	1.5997220	0.5036645	23.03611	190.82290	290.55910	125.09850	2446400.5	0.8	0.794	
2201 Oljato	2.1734010	0.7119996	2.51604	76.43537	95.73036	289.74930	2446400.5	2.8	0.626	
2202 Pele	2.2898010	0.5125682	8.78594	169.75910	217.19640	279.88490	2446400.5	1.2	1.116	
2212 Hephaistos	2.1633440	0.8350517	11.88437	28.02148	208.07170	111.44170	2446400.5	5.4	0.357	U
2329 Orthos	2.4045640	0.6586250	24.39328	168.91690	145.77800	172.72630	2446400.5	3.4	0.821	
2340 Hathor	0.8439506	0.4497948	5.85572	211.09120	39.68816	1.09033	2446400.5	0.2	0.464	U
2368 Beltrovata	2.1046940	0.4131900	5.25833	287.21200	41.93949	256.62640	2446400.5	4.8	1.235	DU
2608 Seneca	2.4787630	0.5864303	15.63621	169.82780	32.45895	346.35280	2446400.5	1.4	1.025	
3102 1981 QA	2.1519100	0.4488226	8.41297	171.77200	154.24070	127.47410	2446400.5	3.2	1.186	
3103 1982 BB	1.4068180	0.3547455	20.94324	129.28680	253.64990	182.28620	2446400.5	5.0	0.908	
3122 1981 ET3	1.7686800	0.4224826	22.18717	335.59200	27.43197	170.87190	2446400.5	6.4	1.021	
3199 1982 RA	1.5746590	0.2837208	32.97512	339.45580	53.24906	194.85380	2446400.5	4.4	1.128	
3200 1983 TB	1.2713230	0.8901712	22.02894	265.04620	321.66790	205.43400	2446400.5	5.0	0.140	

Table 2 Orbital characteristics

Asteroid	Semi-Major Axis (AU)	Eccentricity	Inclination (deg)	Longitude of Ascending Node (deg)	Argument of Perihelion (deg)	Mean Anomaly (deg)	Epoch (Julian Date)	Diameter (km)	Perihelion Distance (AU)	Classification
1937 UB	1.6392658	0.6236360	6.21602	35.32649	90.69590	335.61144	2428834.5	0.0	0.617	lost
1950 DA	1.6833700	0.5019600	12.15000	356.80700	223.59800	340.40700	2433345.5	2.8	0.838	
1954 XA	0.7772000	0.3454000	3.93000	190.31000	57.29000	192.39000	2435080.5	0.8	0.509	
1959 LM	2.1552000	0.6745000	7.64000	295.35000	233.93000	20.18000	2436724.5	0.0	0.702	lost
1972 RB	2.1489380	0.4864589	5.22160	176.90640	152.28920	311.29910	2446000.5	0.8	1.104	
1973 NA	2.4276960	0.6378165	68.01041	100.40350	118.30950	9.39535	2446000.5	6.4	0.879	
1974 MA	1.7573300	0.7598800	37.65300	302.09500	126.80100	359.22400	2442300.5	6.6	0.422	
1977 VA	1.8649610	0.3941550	2.97681	224.03320	172.15220	268.36020	2446000.5	1.6	1.130	
1978 CA	1.1246190	0.2148080	26.11454	160.67360	102.07950	130.01490	2446000.5	1.2	0.883	
1979 QB	2.3300000	0.4423000	3.38000	342.16000	11.34000	354.17000	2444120.5	1.4	1.299	
1979 VA	2.6430460	0.6223492	2.78397	270.33730	90.92438	64.45463	2446000.5	2.6	0.998	
1979 XB	2.2624420	0.7132964	24.86565	85.36106	75.50605	346.38010	2444220.5	0.8	0.649	
1980 AA	1.8912000	0.4442798	4.18733	298.52170	168.03840	303.89090	2446000.5	0.6	1.051	
1980 PA	1.9257780	0.4586429	2.16302	261.68910	125.12860	184.35710	2446000.5	1.0	1.043	
1980 WF	2.2292480	0.5150134	6.41746	241.19150	212.72410	54.74082	2446000.5	1.0	1.081	
1980 YS	1.8152790	0.3211742	2.27866	58.67237	49.00677	9.54138	2444640.5	2.6	1.232	
1981 CW	1.8764020	0.3681529	4.77404	106.96660	15.43939	16.15236	2444680.5	2.6	1.186	
1981 QB	2.2390720	0.5181123	37.16380	154.04230	248.10650	81.35838	2445200.5	3.2	1.079	
1981 VA	2.4594330	0.7438704	22.02026	246.01000	59.40772	18.02412	2444920.5	2.0	0.630	
1982 DB	1.4893150	0.3601671	1.42009	314.08190	157.82810	117.45690	2445200.5	1.0	0.953	
1982 DV	2.0332430	0.4566662	5.92683	218.22290	349.19490	315.48270	2446000.5	4.0	1.105	
1982 FT	1.7742110	0.2837969	20.38330	348.32630	234.51350	16.92771	2446000.5	5.0	1.271	
1982 HR	1.2100110	0.3228060	2.68853	189.23940	301.62500	7.67033	2446000.5	0.8	0.819	
1982 RB	2.1019280	0.3948698	24.99579	158.44700	158.57660	263.05510	2446000.5	2.0	1.272	
1982 TA	2.3029890	0.7710444	12.11626	10.04389	118.59720	187.48330	2446000.5	5.0	0.527	
1982 XB	1.8376670	0.4468762	3.87314	74.57840	16.68247	266.01970	2446000.5	0.6	1.016	
1982 YA	3.7067340	0.6972531	34.57320	269.16220	143.63890	98.26809	2446000.5	2.6	1.122	
1983 LB	2.2914150	0.4786899	25.39914	80.93631	220.15170	128.42990	2446000.5	1.6	1.195	
1983 LC	2.6315180	0.7093340	1.51906	159.06680	184.69150	101.26840	2446000.5	0.8	0.765	
1983 RB	2.2233400	0.5070001	19.42719	168.88440	114.80820	141.71190	2446000.5	3.2	1.096	
1983 RD	2.0901080	0.4866659	9.51734	173.40310	192.94850	129.08140	2446000.5	2.0	1.073	
1983 SA	4.2307220	0.7145723	30.77923	350.02850	316.60390	97.27140	2446400.5	10.2	1.208	
1983 TF2	1.3427630	0.3870827	7.83661	10.43011	121.05230	283.80690	2445620.5	1.6	0.823	
1983 VA	2.6106830	0.6917034	16.23778	76.87026	11.68396	167.10800	2446400.5	2.6	0.805	
1984 KB	2.2210346	0.7622750	4.63662	170.56242	334.87816	61.62574	2446000.5	0.0	0.528	**
1984 KD	2.1975780	0.5408661	13.61579	81.84232	203.58240	155.53560	2446400.5	2.0	1.009	
1984 QA	0.9896304	0.4683812	9.91826	152.04500	54.82670	181.19600	2446400.5	1.2	0.526	
4788 P-L	2.5500000	0.5450000	10.80000	0.00000	0.00000	0.00000	2400000.5	0.0	1.160	lost
6344 P-L	2.5760000	0.6350000	4.61600	184.27000	232.60000	0.00000	2437247.5	0.0	0.821	lost
6743 P-L	1.6197000	0.4931000	7.29000	10.92000	104.68000	0.00000	2437320.5	0.0	0.832	lost

** Asteroid with uncertain orbital elements

Although the optimal transfer to each asteroid can be achieved, its frequency is not high. In the next section, we consider opportunities that can be accomplished between 1990 and 2010 to rendezvous ballistically with the most accessible objects.

Rendezous Missions

In this section, we list opportunities to rendezvous ballistically with the more accessible near-Earth asteroids. Many opportunities have already been identified in the literature[7,9,13–17] for rendezvous missions to individual or selected groups of these objects. Our purpose here is to update the list of opportunities and to include newly discovered objects and launch dates through 2010. The thirty-two near-Earth asteroids for which trajectories were generated were those with a global minimum total ΔV of less than 8.0 km/s.

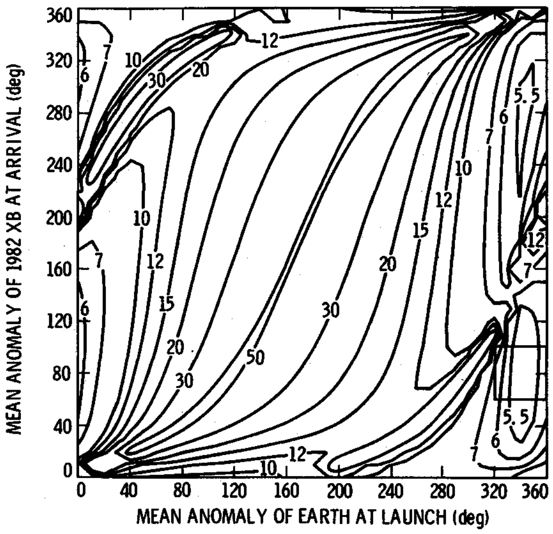

Fig. 1 Contours of minimum total ΔV for two-impulse ballistic transfer from standard shuttle orbit to rendezvous with 1982 XB. The region containing the global minimum is outlined on the bottom right.

Table 3 Ranking of near-Earth asteroids by accessibility

Rank	Asteroid	Global Minimum Total ΔV (km/s)	Mean Anomaly of Earth at Launch (deg)	Mean Anomaly of Asteroid at Arrival (deg)	Time of Flight (days)
1	1982 DB	4.453	19.303	115.101	206
2	1982 XB	5.242	341.415	81.517	211
3	1943 Anteros	5.272	140.052	247.427	390
4	1982 HR	5.294	61.897	143.581	180
5	1980 AA	5.402	10.317	247.980	621
6	1977 VA	5.496	297.954	220.500	529
7	1980 PA	5.613	288.545	294.820	750
8	1981 CW	5.900	11.498	127.618	319
9	1982 DV	5.912	110.881	229.637	636
10	433 Eros	5.947	21.049	181.241	298
11	1980 YS	6.042	350.528	99.580	242
12	2061 Anza	6.054	266.182	290.462	954
13	1627 Ivar	6.117	206.221	236.992	565
14	1972 RB	6.272	235.946	284.028	825
15	1983 RD	6.483	256.969	122.422	376
16	1980 WF	6.554	340.815	68.642	237
17	1979 QB	6.603	245.693	144.368	485
18	1954 XA	6.610	316.086	55.349	165
19	2368 Beltrovata	6.701	209.989	78.383	246
20	1979 VA	6.805	256.325	310.992	1330
**		6.793	257.511	306.335	1324
21	887 Alinda	6.852	2.163	230.511	870
22	3102 1981 QA	6.855	236.442	267.960	744
23	2063 Bacchus	7.105	289.601	189.290	300
24	1221 Amor	7.162	78.793	90.424	252
25	2202 Pele	7.176	270.148	65.247	239
26	2059 Baboquivari	7.476	284.337	140.760	584
27	1685 Toro	7.675	341.062	113.122	164
28	1916 Boreas	7.779	226.901	256.695	756
29	1984 KD	7.798	173.426	92.120	318
30	2100 Ra-shalom	7.949	249.973	0.011	110
31	2340 Hathor	7.955	307.826	23.770	151
32	2062 Aten	7.989	6.465	369.027	127
33	2201 Oljato	8.037	85.438	117.100	414
34	1983 VA	8.160	345.125	121.988	555
35	1620 Geographos	8.537	235.585	-4.011	370
**		8.514	233.800	-9.295	362
36	1862 Apollo	8.631	186.265	249.385	602
37	1950 DA	8.678	81.870	274.605	702
**		8.539	94.481	279.775	714
38	2608 Seneca	8.679	91.923	75.468	310
39	1915 Quetzalcoat	8.705	52.840	224.117	868
40	2101 Adonis	8.741	278.413	204.297	677
**		8.709	288.584	217.286	681

** Three-impulse trajectories

For each year starting with 1990 and ending with 2010, the date corresponding to the launch of the best transfer to each asteroid and its time of flight were used as imputs to the trajectory optimizer. Although the global mimimum transfer was unlikely to occur, one close to it would result in the better years. We note that this search method may not capture an opportunity for a given year if it exists near a minimum other than the global minimum.

Table 5 lists the best rendezvous opportunities within the 21-year period for the thirty-two selected asteroids in terms of the total ΔV. The trajectories are listed in the order of increasing total ΔV for each asteroid. The total ΔV's for these best cases actually come very close to the optimal shown in Tables 3 and 4. Also, the ranking by the best opportunity during this period varies only slightly from the ranking in Tables 3 and 4. The launch energy per unit mass, C_3, for some of these trajectories is excessively high to yield any practical missions. Trajectories with a C_3 of less than 70 km^2/s^2 and a post launch ΔV of less than 3 km/s are considered to be feasible, and these opportunities are listed in Tables 6–12. We do not exclude any opportunities with a long mission duration. We include trajectories with one or more additional midcourse impulses. All of the thirty-two asteroids have at least one feasible opportunity. The opportunities not listed in Tables 6–12 can be obtained from the first author. For a few asteroids, missions with a total ΔV lower than the optimum can be obtained by including an Earth gravity assist maneuver.[17] The tradeoff, however, is the addition of one year to the flight time.

The frequency of feasible opportunities is an important factor when considering an asteroid for extraterrestrial material utilization missions. Table 13 lists the frequency of feasible opportunities for the thirty-two asteroids in terms of the number of opportunities and the average time between them. Although these frequencies are for the 21-year period 1990 to 2010, they are representative of what can be expected for these asteroids in general. To demonstrate that Table 13 is indeed a good indication of frequency, we have extended the search for feasible opportunities for two asteroids for a total of 51 years, 1990 to 2040. 1982 DB, an asteroid with a high frequency of opportunities, and 2063 Bacchus, one with a low frequency, were selected. The number of opportunities for 1982 DB within the 51-year period is thirty-two, and the average time between opportunities is 1.58 years, very close to the 1.50 years calculated for the 21-year period. Similarly, the number of opportunities for 2063 Bacchus is fifteen, and the average

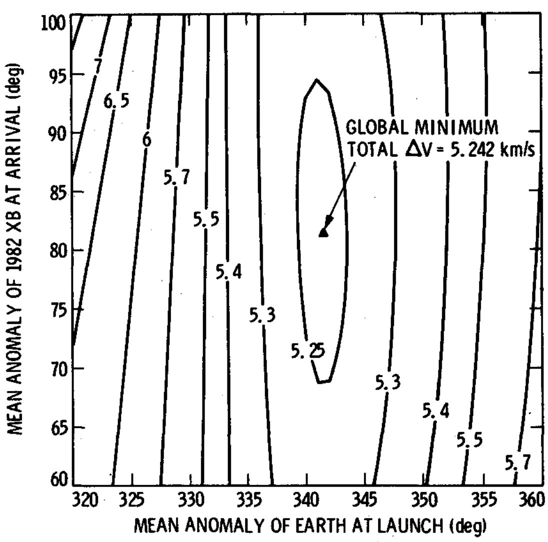

Fig. 2 Global minimum total ΔV found by trajectory optimizer.

time between opportunities is 2.79 years, comparable to the six opportunities and 2.20 years calculated for the 21-year period.

We note that the correlation with rank by the optimal total ΔV is not good. This is not surprising since what constitutes a feasible opportunity depends on launch vehicle technology as well as orbital characteristics. Table 14 lists the asteroids in the increasing order of the average total ΔV times the mean time between opportunities. This ranking correlates better with Tables 3 and 4, since the frequency is weighted by the average total ΔV.

Sample Return Missions

Once again we note that round-trip trajectories to and from near-Earth asteroids have appeared in the literature[9,13,14,18,19] and that our purpose in this section is to update the list and include launch dates through 2010. Sample return opportunities for the ten most accessible near-Earth asteroids were generated. The spacecraft is to rendezvous with the asteroid, land, and return a small sample to Earth. Return opportunities are determined for the outbound rendezvous trajectories with a C_3 of less than 40 km²/s² discussed in the

Table 4 Ranking of near-Earth asteroids by accessibility

Rank	Asteroid	Global Minimum Total ΔV (km/s)	Mean Anomaly of Earth at Launch (deg)	Mean Anomaly of Asteroid at Arrival (deg)	Time of Flight (days)
41	1984 QA	9.380	45.133	194.136	313
42	1917 Cuyo	9.436	272.446	137.407	445
43	3122 1981 ET3	9.480	240.684	111.669	291
44	1865 Cerberus	9.658	120.072	188.352	228
45	1982 FT	9.873	74.975	80.816	226
46	1982 RB	10.138	229.128	233.214	600
47	3103 1982 BB	10.494	210.286	29.490	108
48	1978 CA	10.916	239.831	308.197	300
49	2212 Hephaistos	10.916	156.573	105.169	404
50	1983 LB	10.921	176.277	80.789	303
51	2329 Orthos	11.034	210.833	287.754	1082
52	1982 TA	11.146	-2.223	289.937	1347
**		10.666	20.765	282.752	1222
53	1983 RB	11.201	203.659	312.539	750
54	1036 Ganymed	11.621	266.925	297.191	931
55	1983 SA	11.902	215.019	312.004	2054
56	1982 YA	11.916	319.512	298.243	1733
57	1863 Antinous	12.389	171.850	46.068	151
58	1864 Daedalus	12.465	200.038	262.425	641
59	1980 Tezcatlipoc	12.564	317.586	296.161	435
60	2135 Aristaeus	13.027	75.025	63.078	91
61	3199 1982 RA	13.438	240.640	94.976	238
62	1981 VA	13.447	230.708	51.579	214
63	1979 XB	15.057	94.097	48.619	164
64	1580 Betulia	15.401	131.614	233.759	661
65	1951 Lick	15.663	208.432	224.917	260
66	1981 QB	16.274	244.691	45.733	220
67	1566 Icarus	16.317	322.353	186.273	394
68	3200 1983 TB	17.492	69.600	242.121	660
**		17.242	100.694	256.981	684
69	1974 MA	18.807	278.046	293.521	1012
**		18.017	296.051	297.868	1134
70	1866 Sisyphus	19.165	237.925	302.525	745
**		18.254	177.254	261.614	1273
71	1981 Midas	21.500	222.550	52.908	102
72	1973 NA	24.906	113.659	314.951	888
73	2102 Tantalus	25.968	341.812	91.855	217

** Three-impulse trajectories

Table 6 Feasible rendezvous opportunities, launch years from 1990 to 2010

Asteroid	Launch Energy per Unit Mass, C_3 (km/s)²	Time of Flight (days)	Date of Launch From Earth	Maneuver Date	Date of Arrival at Asteroid	Post-Launch ΔV (km/s)	Total ΔV (km/s)
1982 DB	23.42	578	01/12/91		08/12/92	0.458	4.686
	20.21	607	01/24/93	08/16/93	09/23/94	0.562	4.655
	50.26	403	12/18/94		01/25/96	2.833	8.134
	34.45	899	01/24/96	11/23/97	07/11/98	1.480	6.160
	9.40	475	01/31/97	08/16/97	05/21/98	2.077	5.704
	30.88	737	01/07/98		01/14/00	1.155	5.690
	25.93	646	01/10/00		10/17/01	0.701	5.033
	22.64	640	01/22/02	08/13/02	10/24/03	0.284	4.479
	17.50	573	01/26/04	08/19/04	08/21/05	0.894	4.871
	12.04	507	01/29/06	08/21/06	06/20/07	1.647	5.390
	32.28	873	01/26/07		06/17/09	1.286	5.878
	6.68	440	02/03/08	08/08/08	04/18/09	2.605	6.111
	28.36	693	01/08/09		12/02/10	0.928	5.360
1982 XB	29.47	783	12/09/90		01/30/93	1.304	5.782
	39.51	1112	12/15/92	07/14/93	01/01/96	0.360	5.243
	45.16	642	12/15/92		09/18/94	0.309	5.413
	49.05	1040	12/13/94	04/22/96	10/18/97	1.112	6.367
	28.97	775	12/09/95		01/22/98	1.352	5.809
	39.51	1105	12/15/97	07/14/98	12/24/00	0.361	5.243
	47.48	1054	12/16/99	08/29/00	11/04/02	1.058	6.252
	28.46	768	12/08/00		01/15/03	1.401	5.838
	39.51	1099	12/15/02	07/14/03	12/18/05	0.361	5.243
	47.18	1047	12/15/04	08/27/05	10/28/07	1.035	6.217
	27.95	760	12/08/05		01/07/08	1.451	5.867
	39.45	1079	12/16/07		11/28/10	0.365	5.245
	46.87	1040	12/15/09	08/26/10	10/21/12	1.011	6.181
1943 Anteros	38.84	686	05/26/90	06/06/91	04/10/92	1.015	5.870
	31.68	512	05/25/92	06/17/93	10/19/93	1.027	5.595
	18.95	424	05/29/94	03/30/95	07/27/95	2.679	6.718
	40.87	730	05/25/95	06/26/96	05/25/97	1.444	6.380
	35.91	400	05/24/97		06/29/98	0.537	5.276
	24.72	463	05/28/99	04/28/00	09/03/00	1.842	6.124
	43.24	776	05/24/00	07/20/01	07/09/02	1.816	6.845
	45.31	779	05/26/00	04/30/01	07/13/02	1.767	6.877
	38.49	677	05/26/02	06/02/03	04/02/04	0.916	5.757
	30.52	504	05/26/04	06/08/05	10/11/05	1.155	5.675
	17.84	416	05/29/06	03/26/07	07/20/07	2.875	6.867
	57.27	673	05/25/07	04/19/08	03/27/09	1.298	6.865
	40.40	721	05/26/07	06/22/08	05/15/09	1.360	6.278
	35.71	427	05/24/09		07/25/10	0.595	5.326
1982 HR	16.63	182	03/04/90		09/01/90	1.929	5.869
	17.39	530	01/03/91		06/16/92	2.521	6.494
	21.11	487	10/14/92	01/15/93	02/13/94	2.371	6.502
	18.12	453	03/08/94	08/28/94	06/04/95	1.387	5.391
	20.61	218	03/14/94		10/18/94	1.989	6.115
	17.20	526	01/03/95		06/12/96	2.498	6.463
	21.11	485	10/14/96	01/15/97	02/11/98	2.371	6.502
	30.40	134	01/25/98		06/09/98	2.125	6.641
	21.11	482	10/14/00	01/15/01	02/08/02	2.371	6.502
	37.20	127	01/15/02		05/22/02	2.183	6.973
	16.80	519	01/04/03		06/06/04	2.452	6.400
	21.12	480	10/14/04	01/15/05	02/06/06	2.371	6.502
	42.81	120	01/06/06		05/07/06	2.241	7.253
	16.61	516	01/04/07		06/02/08	2.428	6.368
	21.13	473	10/14/08	01/15/09	01/30/10	2.366	6.497

Table 5 The best rendezvous opportunities, launch years from 1990 to 2010

Asteroid	Launch Energy per Unit Mass, C_3 (km/s)²	Time of Flight (days)	Date of Launch From Earth	Maneuver Date	Date of Arrival at Asteroid	Post-Launch ΔV (km/s)	Total ΔV (km/s)	Rank by Optimal Total ΔV
1982 DB	22.64	640	01/22/02	08/13/02	10/24/03	0.284	4.479	1
1982 XB	39.51	1112	12/15/92	07/14/93	01/01/96	0.360	5.243	2
1943 Anteros	35.91	400	05/24/97		06/29/98	0.537	5.276	3
1982 HR	18.12	453	03/08/94	08/28/94	06/04/95	1.387	5.391	4
1980 AA	40.11	703	01/14/01		12/18/02	0.620	5.526	5
1977 VA	36.91	516	11/01/00	06/27/01	03/31/02	0.755	5.534	6
1980 PA	35.34	746	10/28/07		11/12/09	1.000	5.715	7
1981 CW	36.43	1237	01/15/94	11/29/94	06/04/97	1.140	5.900	8
433 Eros	38.43	292	01/25/05		11/13/05	1.112	5.951	10
1980 YS	28.06	567	12/29/07	08/28/08	07/18/09	1.626	6.046	11
2061 Anza	55.02	947	09/29/01		05/03/04	0.580	6.063	12
1982 DV	46.78	929	04/26/91	12/13/92	11/09/93	0.940	6.107	9
1627 Ivar	51.08	589	07/30/08		03/11/10	0.815	6.148	13
1972 RB	50.12	830	09/02/07		12/10/09	1.039	6.334	14
1980 WF	51.20	234	12/15/90		08/06/91	1.228	6.565	16
1954 XA	39.04	166	11/09/91	01/26/92	04/23/92	1.707	6.571	18
1983 RD	64.18	1101	11/21/89	10/05/90	09/26/92	0.760	6.584	15
1979 QB	53.14	1715	09/09/90	01/07/92	05/21/95	1.192	6.603	17
1979 VA	65.89	1321	09/21/92	05/18/93	05/04/96	0.909	6.796	20
3102 1981 QA	54.44	743	09/01/94		09/13/96	1.435	6.895	22
887 Alinda	69.89	892	01/04/90		06/14/92	0.885	6.918	21
2063 Bacchus	47.78	309	10/25/95		08/28/96	1.904	7.109	23
2368 Beltrovata	46.93	1169	08/04/89	04/21/90	10/15/92	1.978	7.151	19
1221 Amor	59.11	1205	03/23/96	12/01/96	07/11/99	1.526	7.162	24
2202 Pele	57.12	1444	10/04/93	05/30/94	09/16/97	1.615	7.176	25
2059 Baboquivari	70.86	582	10/18/89		05/23/91	1.423	7.491	26
1916 Boreas	62.71	761	08/21/91		09/21/93	2.012	7.782	28
1685 Toro	68.70	443	12/11/07	05/16/08	02/27/09	1.839	7.829	27
1984 KD	67.57	1429	06/27/07	07/31/10	05/26/11	1.915	7.863	29
2340 Hathor	61.12	378	11/11/05	05/04/06	11/24/06	2.244	7.955	31
2062 Aten	99.90	148	01/08/96		06/04/96	1.065	8.147	32
2100 Ra-Shalom	69.39	267	09/14/97	01/05/98	06/08/98	2.253	8.268	30

Table 7 Feasible rendezvous opportunities, launch years from 1990 to 2010

Asteroid	Launch Energy per Unit Mass, C_3 (km/s)^2	Time of Flight (days)	Date of Launch From Earth	Maneuver Date	Date of Arrival at Asteroid	Post-Launch ΔV (km/s)	Total ΔV (km/s)
1982 HR	40.56	351	12/10/09		11/27/10	1.269	6.193
1980 AA	49.56	1117	01/14/90	11/30/91	02/04/93	1.127	6.401
	29.19	711	01/16/91	06/06/92	12/28/92	1.561	6.027
	58.44	1332	01/15/92	04/15/94	09/07/95	1.761	7.372
	42.55	978	01/14/93	09/15/94	09/19/95	0.565	5.567
	67.57	1556	01/16/94	09/02/95	04/21/98	2.215	8.163
	52.75	1188	01/14/95	01/13/97	04/17/98	1.363	6.760
	34.36	785	01/15/96	08/03/97	03/11/98	1.063	5.740
	61.03	1405	01/14/97	06/02/99	11/18/00	1.934	7.641
	46.20	1047	01/14/98	10/21/99	11/26/00	0.867	6.012
	23.64	639	01/18/99	04/13/00	10/18/00	2.147	6.383
	55.78	1259	01/15/00	03/10/02	06/26/03	1.573	7.084
	40.11	703	01/14/01		12/18/02	0.620	5.526
	63.45	1478	01/14/02	07/21/04	01/31/06	2.091	7.888
	49.62	1118	01/14/03	12/01/04	02/06/06	1.133	6.409
	29.30	712	01/17/04	06/08/05	12/29/05	1.550	6.021
	58.56	1333	01/14/05	04/26/07	09/07/08	1.763	7.378
	42.62	979	01/14/06	09/17/07	09/19/08	0.572	5.577
	65.71	1551	01/14/07	09/09/09	04/14/11	2.235	8.115
	52.81	1190	01/15/08	01/14/10	04/19/11	1.368	6.767
	34.46	787	01/15/09	08/04/10	03/12/11	1.055	5.735
	61.08	1406	01/14/10	06/03/12	11/20/13	1.937	7.647
1977 VA	34.91	621	11/06/90		07/19/92	1.016	5.715
	59.76	1411	11/02/91	12/12/93	09/14/95	2.345	8.005
	44.12	1054	11/01/92	05/28/94	09/21/95	1.306	6.370
	21.65	669	11/03/93	01/11/95	09/03/95	2.292	6.446
	53.38	1248	11/02/94	09/09/96	04/03/98	1.942	7.362
	36.35	587	11/03/95		06/12/97	0.814	5.570
	60.96	1445	11/02/96	01/01/99	10/17/00	2.418	8.123
	45.85	1087	11/02/97	06/14/99	10/23/00	1.430	6.561
	24.24	699	11/03/98	01/25/00	10/02/00	1.992	6.254
	54.79	1282	11/02/99	09/28/01	05/07/03	2.033	7.507
	36.91	516	11/01/00	06/27/01	03/31/02	0.755	5.534
	47.52	1120	11/02/02	07/01/04	11/26/05	1.547	6.743
	26.76	731	11/03/03	02/11/05	11/03/05	1.716	6.082
	56.15	1316	11/02/04	10/18/06	06/09/08	2.120	7.645
	38.88	961	11/01/05	04/16/07	06/20/08	0.912	5.769
	28.08	1491	11/03/06	02/21/10	12/03/10	1.565	5.986
	49.12	1153	11/02/07	07/19/09	12/30/10	1.658	6.916
	29.21	763	11/02/08	03/02/10	12/05/10	1.460	5.927
	57.46	1349	11/02/09	11/07/11	07/13/13	2.203	7.777
1980 PA	51.85	1241	10/20/90	05/14/91 06/14/93 *	03/13/94	1.638	7.000
	34.65	741	10/29/91		11/07/93	1.060	5.748
	61.26	1481	10/20/92	06/14/93 01/09/96 *	11/09/96	2.209	7.925
	46.43	1128	10/19/93	05/01/94 03/05/96 *	11/19/96	1.276	6.430
	68.80	1724	10/21/94	07/14/95 08/07/98 *	07/10/99	2.630	8.624
	27.32	657	11/05/94		08/23/96	1.751	6.141
	56.95	1363	10/20/95	05/30/96 09/29/98 *	07/15/99	1.954	7.509

* Additional maneuver date

Table 8 Feasible rendezvous opportunities, launch years from 1990 to 2010

Asteroid	Launch Energy per Unit Mass, C_3 (km/s)^2	Time of Flight (days)	Date of Launch From Earth	Maneuver Date	Date of Arrival at Asteroid	Post-Launch ΔV (km/s)	Total ΔV (km/s)
1980 PA	57.19	1370	10/20/03	05/30/04 10/04/06 *	07/21/07	1.969	7.533
	40.72	805	10/16/04	04/21/05	12/30/06	0.868	5.798
	65.52	1611	10/20/05	06/30/06 05/01/09 *	03/20/10	2.450	8.324
	52.40	1253	10/20/06	05/16/07 06/25/09 *	03/26/10	1.672	7.055
	35.34	746	10/28/07		11/12/09	1.000	5.715
	61.69	1493	10/20/08	06/15/09 01/20/12 *	11/21/12	2.234	7.966
	47.02	1139	10/19/09	04/30/10 03/17/12 *	12/01/12	1.319	6.495
1981 CW	43.45	1046	01/15/91	01/05/92	11/26/93	1.710	6.747
	21.55	612	02/02/92	09/26/92	10/06/93	2.867	7.016
	36.43	1237	01/15/94	11/29/94	06/04/97	1.140	5.900
	45.93	1097	01/16/96	01/21/97	01/17/99	1.891	7.025
	30.34	1077	01/14/97	02/14/99	12/27/99	1.685	6.198
	37.93	940	01/15/99	12/01/99	08/12/01	1.282	6.101
	48.29	1148	01/15/01	02/07/02	03/08/04	2.056	7.281
	36.89	1017	01/10/02		10/24/04	1.393	6.171
	40.69	991	01/16/04	12/17/04	10/03/06	1.501	6.430
	50.53	1200	01/15/06	02/24/07	04/29/09	2.209	7.520
	36.42	1182	01/15/07	11/29/07	04/11/10	1.141	5.900
	43.31	1043	01/15/09	01/03/10	11/24/11	1.700	6.731
	21.43	608	02/02/10	09/27/10	10/03/11	2.890	7.034
1982 DV	62.61	1321	04/26/90	06/02/92	12/07/93	1.449	7.215
	46.78	929	04/26/91	12/13/92	11/09/93	0.940	6.107
	61.26	1285	04/26/93	05/13/95	10/31/96	1.353	7.069
	44.55	892	04/26/94	11/18/95	10/04/96	1.127	6.207
	59.86	1248	04/26/96	04/21/98	09/26/99	1.251	6.915
	42.20	855	04/26/97	10/24/98	08/29/99	1.329	6.317
	58.42	1212	04/27/99	03/31/01	08/21/02	1.144	6.754
	39.73	818	04/26/00	09/28/01	07/23/02	1.547	6.438
	56.92	1176	04/26/02	03/10/04	07/16/05	1.031	6.585
	42.14	691	05/06/03		03/27/05	1.730	6.716
	68.65	1500	04/26/04	09/21/06	06/04/08	1.861	7.849
	55.38	1141	04/26/05	02/19/07	06/10/08	0.911	6.407
	34.40	745	04/27/06	08/11/07	05/11/08	2.040	6.718
	67.50	1464	04/26/07	08/29/09	04/29/11	1.785	7.731
	53.79	1105	04/26/08	01/31/10	05/06/11	0.783	6.219
	31.54	708	04/27/09	07/18/10	04/06/11	2.320	6.882

* Additional maneuver date

Table 9 Feasible rendezvous opportunities, launch years from 1990 to 2010

Asteroid	Launch Energy per Unit Mass, C_3 (km/s)^2	Time of Flight (days)	Date of Launch From Earth	Maneuver Date	Date of Arrival at Asteroid	Post-Launch ΔV (km/s)	Total ΔV (km/s)
433 Eros	36.31	609	01/23/91	11/19/91	09/23/92	1.403	6.157
	28.17	524	01/20/93	10/25/93	06/28/94	2.553	6.978
	44.50	784	01/25/94	01/15/95	03/19/96	2.443	7.521
	40.92	697	01/26/96	12/06/96	12/23/97	1.780	6.718
	48.46	873	02/07/97	05/30/98	06/30/99	2.672	7.904
	42.09	338	01/21/98		12/25/98	1.115	6.098
	29.66	540	01/21/00	10/29/00	07/14/01	2.319	6.804
	45.20	799	01/25/01	01/22/02	04/04/03	2.547	7.653
	41.53	713	01/26/03	12/14/03	01/08/05	1.913	6.875
	38.43	292	01/25/05		11/13/05	1.112	5.951
	31.17	555	01/21/07	11/03/07	07/29/08	2.096	6.644
	45.89	815	01/26/08	01/29/09	04/20/10	2.648	7.780
	42.17	729	01/26/10	12/21/10	01/24/12	2.040	7.027
1980 YS	27.79	591	01/09/91	09/15/91	08/22/92	1.728	6.137
	33.55	980	12/24/92	09/06/93	08/30/95	2.151	6.794
	26.48	581	01/18/96	09/25/96	08/21/97	1.907	6.262
	31.20	940	12/23/97	08/28/98	07/20/00	1.981	6.529
	40.29	1103	12/26/99	10/02/00	01/02/03	2.604	7.517
	24.70	560	01/25/01	10/05/01	08/08/02	2.127	6.408
	28.75	900	12/23/02	08/20/03	06/10/05	1.797	6.245
	38.21	1064	12/25/04	09/24/05	11/23/07	2.469	7.300
	22.64	532	02/02/06	10/14/06	07/19/07	2.377	6.572
	28.06	567	12/29/07	08/28/08	07/18/09	1.626	6.046
	36.05	1024	12/24/09	09/16/10	10/13/12	2.325	7.069
2061 Anza	64.87	1519	09/29/90	11/16/93	11/27/94	1.211	7.061
	53.27	977	10/03/91		06/06/94	0.722	6.138
	33.82	700	10/16/92		09/16/94	2.370	7.038
	69.34	1665	09/29/93	03/15/97	04/22/98	1.474	7.487
	57.29	1314	09/28/94	06/04/97	05/04/98	0.738	6.306
	43.32	836	10/10/95		01/23/98	1.540	6.572
	62.68	1455	09/29/97	09/25/00	09/23/01	1.078	6.847
	50.82	949	10/05/98		05/11/01	0.935	6.257
	67.41	1600	09/29/00	01/22/04	02/15/05	1.361	7.304
	55.02	947	09/29/01		05/03/04	0.580	6.063
	60.35	1391	09/28/04	08/05/07	07/20/08	0.933	6.616
	47.77	903	10/07/05		03/28/08	1.183	6.388
	65.37	1535	09/30/07	11/29/10	12/12/11	1.240	7.108
	53.70	978	10/02/08		06/07/11	0.680	6.112
1627 Ivar	52.92	980	08/01/90	02/28/92	04/07/93	1.069	6.471
	60.99	1170	07/31/92	06/10/94	10/14/95	1.833	7.539
	44.22	764	08/01/93	12/21/94	09/04/95	1.401	6.468
	54.22	1009	08/01/95	03/13/97	05/06/98	1.208	6.660
	33.34	564	08/07/96	05/27/97	02/22/98	2.773	7.408
	62.17	1201	07/31/97	06/28/99	11/13/00	1.931	7.681
	46.44	796	07/31/98	01/13/00	10/04/00	1.198	6.352
	55.52	1039	07/31/00	03/29/02	06/05/03	1.339	6.841
	65.76	1055	08/04/00	09/01/01	06/25/03	1.162	7.044
	32.94	630	08/03/01	09/19/02	04/25/03	2.502	7.121
	63.33	1231	08/01/02	07/15/04	12/14/05	2.025	7.817
	48.52	827	07/31/03	02/03/05	11/04/05	1.010	6.245
	56.81	1069	08/01/05	04/15/07	07/04/08	1.463	7.013
	35.76	661	08/03/06	10/10/07	05/25/08	2.212	6.945
	64.45	1262	08/01/07	08/03/09	01/13/11	2.114	7.948
	51.08	589	07/30/08		03/11/10	0.815	6.148

Table 10 Feasible rendezvous opportunities, launch years from 1990 to 2010

Asteroid	Launch Energy per Unit Mass, C_3 (km/s)^2	Time of Flight (days)	Date of Launch From Earth	Maneuver Date	Date of Arrival at Asteroid	Post-Launch ΔV (km/s)	Total ΔV (km/s)
1972 RB	65.28	1512	08/29/90	08/24/93	10/19/94	1.884	7.749
	51.28	831	08/28/91		12/06/93	1.014	6.354
	67.02	1565	08/29/93	10/06/96	12/11/97	1.984	7.913
	53.66	1222	08/28/94	01/07/97	01/01/98	1.173	6.603
	38.25	758	09/09/95	06/07/97	10/06/97	2.077	6.909
	68.67	1619	08/29/96	11/18/99	02/03/01	2.078	8.067
	55.96	1270	08/28/97	02/14/00	02/18/01	1.320	6.837
	41.64	814	09/07/98	07/24/00	11/28/00	1.770	6.737
	58.14	1320	08/28/00	03/26/03	04/10/04	1.457	7.057
	46.34	787	09/06/01		11/02/03	1.451	6.600
	60.22	1372	08/29/03	05/05/06	06/01/07	1.585	7.262
	48.60	816	09/04/04		11/29/06	1.221	6.459
	62.20	1424	08/29/06	06/15/09	07/23/10	1.704	7.455
	50.12	830	09/02/07		12/10/09	1.039	6.334
	64.08	1477	08/29/09	07/27/12	09/14/13	1.815	7.635
1983 RD	46.11	783	09/15/90	08/07/91	11/05/92	2.285	7.426
	64.43	1109	09/21/92	10/08/93	10/05/95	0.789	6.622
	46.70	790	09/15/93	08/08/94	11/14/95	2.231	7.395
	64.68	1118	09/21/95	10/11/96	10/13/98	0.817	6.660
	47.29	798	09/15/96	08/09/97	11/22/98	2.177	7.364
	64.93	1126	09/21/98	10/15/99	10/21/01	0.845	6.697
	47.86	806	09/16/99	08/09/00	11/30/01	2.125	7.334
	65.18	1134	09/21/01	10/19/02	10/29/04	0.873	6.734
	48.42	814	09/16/02	08/11/03	12/08/04	2.073	7.304
	50.60	516	09/17/04		02/14/06	2.728	8.042
	48.98	822	09/16/05	08/12/06	12/16/07	2.023	7.275
	65.67	1150	09/21/07	10/25/08	11/14/10	0.927	6.806
	49.52	830	09/15/08	08/13/09	12/24/10	1.974	7.247
1980 WF	51.20	234	12/15/90		08/06/91	1.228	6.565
	46.38	951	02/03/91		07/12/94	2.002	7.153
	56.46	1292	12/14/93	09/07/94	06/28/97	1.486	7.023
	47.38	1176	12/11/94	08/31/97	03/01/98	1.590	6.780
	60.47	1419	12/14/96	09/30/97	11/02/00	1.742	7.429
	52.45	1308	12/13/97		07/13/01	1.183	6.568
	53.75	261	12/14/00		09/01/01	1.186	6.621
	40.44	1057	12/08/01	04/29/04	10/30/04	2.159	7.078
	56.27	1286	12/15/03	09/05/04	06/23/07	1.473	7.003
	47.10	1171	12/11/04	08/26/07	02/24/08	1.612	6.791
	60.30	1413	12/15/06	09/30/07	10/28/10	1.731	7.411
	52.51	1297	12/13/07		07/03/11	1.187	6.574
1979 QB	53.14	1715	09/09/90	01/07/92	05/21/95	1.192	6.603
	58.37	1391	09/09/93	02/15/95	07/01/97	1.515	7.123
	50.24	780	10/01/94		11/19/96	2.006	7.306
	65.36	1593	09/09/96	04/27/98	01/19/01	1.913	7.781
	53.14	1756	09/09/97	01/07/99	07/01/02	1.192	6.603
	59.89	1432	09/09/00	03/01/02	08/11/04	1.604	7.270
	50.25	1595	09/09/01	09/22/04	01/21/06	1.394	6.695
	66.64	1634	09/10/03	05/12/05	03/01/08	1.983	7.897
	53.54	451	09/09/04		12/03/05	1.267	6.693
	36.56	804	09/29/05	11/14/06	12/12/07	2.796	7.560
	61.37	1473	09/10/07	03/16/09	09/22/11	1.689	7.409
	52.25	1635	09/09/08	11/03/11	03/02/13	1.255	6.632

Table 11 Feasible rendezvous opportunities, launch years from 1990 to 2010

Asteroid	Launch Energy per Unit Mass, C_3 $(km/s)^2$	Time of Flight (days)	Date of Launch From Earth	Maneuver Date	Date of Arrival at Asteroid	Post-Launch ΔV (km/s)	Total ΔV (km/s)
1954 XA	39.04	166	11/09/91	01/26/92	04/23/92	1.707	6.571
	36.55	159	11/22/02		04/30/03	2.108	6.872
	48.29	170	11/03/04	01/28/05	04/22/05	1.378	6.603
2368 Beltrovata	32.16	696	09/02/90	04/04/91	07/30/92	2.990	7.578
	47.83	1189	08/03/92	04/24/93	11/05/95	2.035	7.242
	33.18	715	08/31/93	04/04/94	08/15/95	2.876	7.505
	34.18	732	08/28/96	04/04/97	08/31/98	2.765	7.434
	35.12	750	08/27/99	04/04/00	09/15/01	2.658	7.365
	36.06	768	08/24/02	04/06/03	09/30/04	2.553	7.298
	36.96	785	08/22/05	04/06/06	10/16/07	2.452	7.232
	37.83	802	08/20/08	04/07/09	10/31/10	2.353	7.168
1979 VA	65.89	1321	09/21/92	05/18/93	05/04/96	0.909	6.796
	68.45	1442	09/18/96	05/11/97	08/31/00	0.946	6.927
	61.60	1382	09/21/01	01/15/05	07/04/05	1.208	6.937
	65.11	1308	09/22/05	06/07/06	04/22/09	0.964	6.823
	67.25	1374	09/20/09	05/03/10	06/25/13	0.903	6.840
887 Alinda	69.89	892	01/04/90		06/14/92	0.885	6.918
	54.41	988	01/07/91	09/13/92	09/21/93	2.109	7.569
	67.28	1331	01/05/94	04/26/96	08/28/97	0.980	6.919
	53.28	965	01/07/95	08/30/96	08/29/97	2.210	7.627
	66.59	1308	01/05/98	04/11/00	08/05/01	1.040	6.953
	52.12	942	01/08/99	08/15/00	08/06/01	2.316	7.688
	65.87	1285	01/05/02	03/27/04	07/13/05	1.101	6.988
	50.90	919	01/08/03	07/31/04	07/15/05	2.426	7.752
	65.14	1262	01/05/06	03/11/08	06/20/09	1.165	7.024
	49.63	896	01/08/07	07/16/08	06/22/09	2.542	7.819
	64.38	1239	01/06/10	02/25/12	05/28/13	1.230	7.062
3102 1981 QA	62.27	1373	08/30/90	02/20/93	06/02/94	2.134	7.888
	56.04	744	09/03/91		09/16/93	1.562	7.083
	64.22	1427	08/30/93	03/30/96	07/27/97	2.252	8.078
	54.44	743	09/01/94		09/13/96	1.435	6.895
	66.08	1482	08/30/96	05/09/99	09/20/00	2.363	8.257
	53.13	755	08/29/97		09/23/99	1.488	6.898
	67.85	1538	08/30/99	06/18/02	11/15/03	2.466	8.425
	53.09	804	08/24/00		11/06/02	1.833	7.243
	40.64	736	09/07/01	02/21/03	09/12/03	2.758	7.685
	69.54	1594	08/30/02	07/28/05	01/10/07	2.563	8.583
	57.24	1246	08/30/03	11/25/05	01/26/07	1.815	7.380
	44.35	792	09/05/04	04/07/06	11/06/06	2.390	7.462
	59.42	1298	08/30/06	12/31/08	03/20/10	1.955	7.603
	47.69	848	09/04/07	05/23/09	12/31/09	2.067	7.269
	61.50	1352	08/30/09	02/07/12	05/13/13	2.086	7.811
2063 Bacchus	47.78	309	10/25/95		08/28/96	1.904	7.109
	39.55	385	10/28/96		11/18/97	2.579	7.462
	42.92	441	10/18/03	06/13/04	01/01/05	2.568	7.584
	56.76	264	10/20/04		07/12/05	1.633	7.181
	41.50	356	10/27/05		10/18/06	2.305	7.266
	38.93	422	10/30/06		12/25/07	2.923	7.782
1221 Amor	57.38	1079	03/22/91	07/28/93	03/06/94	1.744	7.315
	60.16	1019	03/25/93	01/18/94	01/08/96	1.975	7.650
	59.83	783	03/14/94	12/21/94	05/05/96	2.278	7.941
	59.11	1205	03/23/96	12/01/96	07/11/99	1.526	7.162

Table 12 Feasible rendezvous opportunities, launch years from 1990 to 2010

Asteroid	Launch Energy per Unit Mass, C_3 $(km/s)^2$	Time of Flight (days)	Date of Launch From Earth	Maneuver Date	Date of Arrival at Asteroid	Post-Launch ΔV (km/s)	Total ΔV (km/s)
1221 Amor	57.08	1074	03/22/99	07/23/01	03/01/02	1.769	7.329
	60.03	1014	03/25/01	01/16/02	01/02/04	1.956	7.626
	59.43	776	03/14/02	12/19/02	04/28/04	2.316	7.964
	61.17	1186	03/23/04	11/19/04	06/22/07	1.454	7.167
	56.77	1070	03/22/07	07/18/09	02/24/10	1.795	7.343
	59.89	1008	03/25/09	01/14/10	12/27/11	1.937	7.602
	59.02	770	03/14/10	12/18/10	04/22/12	2.354	7.987
2202 Pele	55.91	1250	10/01/90	08/25/93	03/04/94	1.782	7.297
	57.12	1444	10/04/93	05/30/94	09/16/97	1.615	7.176
	56.82	946	09/21/94	05/30/94	04/24/97	2.322	7.872
	60.67	1306	10/03/96	07/02/97	05/01/00	1.858	7.552
	54.68	1225	09/30/97	07/31/00	02/07/01	1.873	7.342
	57.12	1418	10/04/00	05/30/01	08/21/04	1.614	7.176
	55.45	915	09/20/01		03/23/04	2.460	7.957
	59.82	1276	10/04/03	06/26/04	04/02/07	1.804	7.466
	53.43	1200	09/30/04	07/06/07	01/13/08	1.968	7.390
	57.12	1392	10/04/07	05/30/08	07/28/11	1.614	7.176
	42.70	1017	09/25/08	12/25/10	07/08/11	2.861	7.869
2059 Baboquivari	59.58	1197	10/15/90	02/09/92	01/24/94	2.510	8.163
	69.37	790	10/08/93		12/07/95	2.914	8.928
	63.59	1313	10/16/94	03/14/96	05/21/98	2.109	7.912
	67.14	1428	10/17/98	04/16/00	09/15/02	1.763	7.696
	58.96	1180	10/15/03	02/03/05	01/08/07	2.572	8.203
	63.04	1296	10/17/07	03/09/09	05/05/11	2.163	7.945
1685 Toro	66.40	456	12/09/91	05/12/92	03/09/93	1.987	7.893
	54.36	416	12/26/93	06/11/94	02/15/95	2.837	8.294
	66.38	487	12/19/96	06/05/97	04/21/98	1.999	7.905
	67.53	450	12/10/99	05/14/00	03/04/01	1.914	7.861
	66.07	485	12/20/04	06/05/05	04/19/06	2.022	7.915
	68.70	443	12/11/07	05/16/08	02/27/09	1.839	7.829
	53.44	412	12/27/09	06/10/10	02/11/11	2.904	8.326
1916 Boreas	62.71	761	08/21/91		09/21/93	2.012	7.782
	61.65	921	08/10/94		02/17/97	2.990	8.720
	57.26	900	08/24/95	04/20/97	02/10/98	2.752	8.319
	65.61	741	08/21/98		08/31/00	2.008	7.885
	60.71	863	08/14/01		12/24/03	2.606	8.302
	69.01	1446	08/20/04	02/24/07	08/05/08	2.590	8.591
	61.28	1001	08/22/05	07/08/07	05/19/08	2.288	8.005
	61.29	807	08/18/08		11/03/10	2.235	7.953
1984 KD	67.57	1429	06/27/07	07/31/10	05/26/11	1.915	7.863
2100 Ra-Shalom	69.39	267	09/14/97	01/05/98	06/08/98	2.253	8.268
2340 Hathor	57.21	148	11/12/94		04/10/95	2.397	7.962
	53.15	141	11/15/01		04/05/02	2.745	8.156
	61.12	378	11/11/05	05/04/06	11/24/06	2.244	7.955
2062 Aten	29.32	187	01/06/97		07/12/97	1.430	9.474
	11.28	321	07/05/08		05/22/09	2.650	10.112

Table 13 Frequency of feasible opportunities, launch years from 1990 to 2010, rank by mean time between opportunities

Asteroid	Number of Opportunities	Mean Time Between Opportunities (years)	Average Total ΔV Times Mean Time	Rank by Optimal Total ΔV
1980 AA	21	1.00	6.68	5
1980 PA	20	1.00	6.97	7
1977 VA	19	1.06	7.01	6
1627 Ivar	16	1.20	8.38	13
1982 DV	16	1.27	8.56	9
1982 HR	16	1.32	8.46	4
1972 RB	15	1.36	9.59	14
3102 1981 QA	15	1.36	10.37	22
2061 Anza	14	1.39	9.23	12
1943 Anteros	14	1.46	9.02	3
1982 DB	13	1.50	8.32	1
1983 RD	13	1.50	10.72	15
1980 WF	12	1.54	10.69	16
1982 XB	13	1.58	9.11	2
433 Eros	13	1.58	10.98	10
1981 CW	13	1.59	10.51	8
1979 QB	12	1.64	11.67	17
2202 Pele	11	1.80	13.45	25
1980 YS	11	1.90	12.56	11
1221 Amor	11	1.90	14.34	24
887 Alinda	11	2.00	14.61	21
2063 Bacchus	6	2.20	16.30	23
1916 Boreas	8	2.43	19.89	28
2368 Beltrovata	8	2.57	18.87	19
1685 Toro	7	3.01	24.08	27
2059 Baboquivari	6	3.40	27.69	26
1979 VA	5	4.25	29.17	20
2340 Hathor	3	5.50	44.13	31
1954 XA	3	6.49	43.39	18
2062 Aten	2	11.49	112.56	32
1984 KD	1	******		29
2100 Ra-Shalom	1	******		30

Table 14 Frequency of feasible opportunities, launch years from 1990 to 2010, rank by average total 5 times mean time between opoportunities

Asteroid	Average Total ΔV Times Mean Time	Rank by Optimal Total ΔV
1980 AA	6.68	5
1980 PA	6.97	7
1977 VA	7.01	6
1982 DB	8.32	1
1627 Ivar	8.38	13
1982 HR	8.46	4
1982 DV	8.56	9
1943 Anteros	9.02	3
1982 XB	9.11	2
2061 Anza	9.23	12
1972 RB	9.59	14
3102 1981 QA	10.37	22
1981 CW	10.51	8
1980 WF	10.69	16
1983 RD	10.72	15
433 Eros	10.98	10
1979 QB	11.67	17
1980 YS	12.56	11
2202 Pele	13.45	25
1221 Amor	14.34	24
887 Alinda	14.61	21
2063 Bacchus	16.30	23
2368 Beltrovata	18.87	19
1916 Boreas	19.89	28
1685 Toro	24.08	27
2059 Baboquivari	27.69	26
1979 VA	29.17	20
1954 XA	43.39	18
2340 Hathor	44.13	31
2062 Aten	112.56	32
1984 KD	******	29
2100 Ra-Shalom	******	30

previous section. Round-trip opportunities with a stay time at the asteroid of over 30 days and less than one year are included. In this search for return opportunities, the stay time is optimized. Due to the design of the trajectory optimizer, a feasible return trip with a stay time of less than a year cannot be found for some of the outbound opportunities mentioned earlier. In one case, 1982 XB, no return trajectory has been discovered. Another method was used to find sample return opportunities for these cases. In this alternative procedure, the entire round-trip mission is optimized, but the stay time at the asteroid is fixed. We varied the stay time from 30 to 360 days at 30-day intervals for each mission and selected the best for

Table 15 Round trip opportunities, launch years from 1990 to 2010

Asteroid	Date of Launch From Earth	Launch Energy per unit Mass, C_3 (km/s)^2	Maneuver Date	Time of Flight (days)	Date of Arrival at Asteroid	Post-Launch ΔV (km/s)	Stay Time (days)	Date of Departure at Asteroid	Departure ΔV (km/s)	Time of Flight (days)	Date of Arrival at Earth	Length of Mission Days	Length of Mission Years
1982 DB	01/12/91	23.42		578	08/12/92	0.458	108	11/28/92	0.777	801	02/07/95	1487	4.07
	01/24/93	20.21	08/16/93	607	09/23/94	0.562	60	11/22/94	1.310	776	01/06/97	1443	3.95
	01/06/96	35.35		813	03/28/98	1.549	120	07/26/98	0.668	567	02/13/00	1500	4.11
	01/31/97	9.40	08/16/97	475	05/21/98	2.077	38	06/28/98	1.957	920	01/03/01	1433	3.92
	01/07/98	30.88		737	01/14/00	1.155	222	08/23/00	0.083	534	02/08/02	1492	4.08
	01/10/00	25.93		646	10/17/01	0.701	70	12/26/01	0.565	774	02/07/04	1489	4.08
	01/22/02	22.64	08/13/02	640	10/24/03	0.284	70	01/02/04	1.127	738	01/09/06	1448	3.96
	01/26/04	17.50	08/19/04	573	08/21/05	0.894	53	10/13/05	1.495	814	01/06/08	1440	3.94
	01/29/06	12.04	08/21/06	507	06/20/07	1.647	43	08/02/07	1.817	886	01/04/10	1436	3.93
	01/06/07	33.05		774	02/18/09	1.353	180	08/17/09	0.339	548	02/16/11	1502	4.11
	02/03/08	5.96	08/15/08	433	04/11/09	2.663	60	06/10/09	2.139	965	01/31/12	1458	3.99
	01/08/09	28.36		693	12/02/10	0.928	45	01/16/11	0.336	753	02/07/13	1490	4.08
1982 XB	12/20/90	26.61	06/10/91	689	11/08/92	1.591	90	02/06/93	1.142	671	12/09/94	1450	3.97
	12/15/92	39.51	07/17/93	783	02/06/95	0.394	150	07/06/95	2.750	520	12/07/96	1452	3.98
	12/10/95	28.54	09/03/96	757	01/04/98	1.396	30	02/03/98	1.101	673	12/09/99	1460	4.00
	12/16/97	39.40	07/17/98	776	02/01/00	0.422	150	06/30/00	2.675	526	12/07/01	1452	3.98
	12/09/00	28.14	09/13/01	753	12/31/02	1.435	30	01/30/03	1.057	678	12/08/04	1461	4.00
	12/17/02	39.29	07/16/03	770	01/25/05	0.451	150	06/24/05	2.603	531	12/07/06	1451	3.97
	12/27/05	27.40		628	09/16/07	1.751	180	03/14/08	1.392	628	12/01/09	1435	3.93
	12/17/07	38.47	07/15/08	794	02/19/10	0.499	120	06/19/10	2.532	537	12/08/11	1451	3.97
1943 Anteros	05/12/90	30.45	02/21/91	458	08/13/91	2.191	270	05/09/92	2.985	382	05/26/93	1110	3.04
	05/25/92	31.68	06/17/93	512	10/19/93	1.027	135	03/03/94	1.211	449	05/26/95	1096	3.00
	05/30/94	19.03	03/21/95	419	07/23/95	2.676	30	08/22/95	0.311	644	05/27/97	1093	2.99
	05/24/97	35.91		400	06/29/98	0.537	269	03/25/99	1.924	426	05/25/00	1096	3.00
	05/28/99	24.72	04/28/00	463	09/03/00	1.842	233	04/24/01	0.492	398	05/27/02	1094	3.00
	05/17/02	32.49	09/30/02	396	06/17/03	2.228	330	05/12/04	2.875	383	05/30/05	1110	3.04
	05/26/04	30.52	06/08/05	504	10/11/05	1.155	142	03/02/06	1.076	451	05/26/07	1096	3.00
	05/30/06	17.91	03/14/07	410	07/14/07	2.873	30	08/13/07	0.406	653	05/27/09	1093	2.99
	05/24/09	35.71		427	07/25/10	0.595	237	03/19/11	1.765	432	05/25/12	1096	3.00
1982 HR	03/04/90	16.63		182	09/01/90	1.929	273	06/01/91	1.402	673	04/04/93	1128	3.09
	01/03/91	17.39		530	06/16/92	2.521	325	05/07/93	0.309	340	04/12/94	1195	3.27
	01/03/95	17.20		526	06/12/96	2.498	133	10/23/96	0.365	385	11/12/97	1044	2.86
	01/25/98	30.40		134	06/09/98	2.125	352	05/27/99	1.444	678	04/04/01	1164	3.19
	01/13/02	36.60		118	05/11/02	2.250	30	06/10/02	2.827	322	04/28/03	470	1.29
	01/04/03	16.80		519	06/06/04	2.452	135	10/19/04	0.276	390	11/12/05	1044	2.86
	01/04/07	16.61		516	06/02/08	2.428	275	03/04/09	0.937	243	11/01/09	1033	2.83
1980 AA	01/19/91	29.56	05/10/92	687	12/06/92	1.553	120	04/05/93	1.665	647	01/12/95	1454	3.98
	01/19/96	36.12		687	12/05/97	1.054	180	06/03/98	2.293	588	01/12/00	1455	3.98
	01/18/99	23.64	04/13/00	639	10/18/00	2.147	254	06/29/01	2.752	469	10/10/02	1361	3.73
	01/17/04	29.30	06/08/05	712	12/29/05	1.550	135	05/13/06	1.872	621	01/24/08	1468	4.02
	01/18/09	36.21		688	12/07/10	1.044	180	06/05/11	2.306	587	01/11/13	1455	3.98

Table 16 Round trip opportunities, launch years from 1990 to 2010

Asteroid	Date of Launch From Earth	Launch Energy per unit Mass, C_3 (km/s)^2	Maneuver Date	Time of Flight (days)	Date of Arrival at Asteroid	Post-Launch ΔV (km/s)	Stay Time (days)	Date of Departure at Asteroid	Departure ΔV (km/s)	Time of Flight (days)	Date of Arrival at Earth	Length of Mission Days	Length of Mission Years
1977 VA	11/06/90	34.91		621	07/19/92	1.016	210	02/14/93	0.400	996	11/07/95	1827	5.00
	11/03/93	21.65	01/11/95	669	09/03/95	2.292	156	02/06/96	1.296	628	10/26/97	1454	3.98
	11/03/95	36.35		587	06/12/97	0.814	282	03/21/98	0.243	962	11/06/00	1831	5.01
	10/29/98	24.60	03/07/00	747	11/13/00	1.987	90	02/11/01	1.539	619	10/24/02	1456	3.99
	11/02/00	38.88	03/30/01	426	01/03/02	0.768	360	12/29/02	1.675	683	11/11/04	1469	4.02
	11/03/03	26.76	02/11/05	731	11/03/05	1.716	117	02/28/06	1.799	601	10/22/07	1449	3.97
	11/01/05	38.88	04/16/07	961	06/20/08	0.912	350	06/05/09	0.703	518	11/05/10	1829	5.01
	11/03/06	28.08	02/21/10	1491	12/03/10	1.565	106	03/19/11	2.079	580	10/19/12	2177	5.96
1980 PA	10/29/91	34.65		741	11/07/93	1.060	348	10/21/94	0.024	734	10/24/96	1822	4.99
	10/28/99	34.99		743	11/10/01	1.029	146	04/05/02	3.022	525	09/12/03	1415	3.87
	10/28/07	35.34		746	11/12/09	1.000	149	04/10/10	3.084	519	09/11/11	1414	3.87
1981 CW	02/02/92	21.55	09/26/92	612	10/06/93	2.867	241	06/04/94	1.650	583	01/08/96	1436	3.93
	01/15/94	36.43	11/29/94	1237	06/04/97	1.140	222	01/12/98	1.530	366	01/13/99	1825	5.00
	01/15/99	37.93	12/01/99	940	08/12/01	1.282	77	10/28/01	4.231	422	12/24/02	1439	3.94
	02/02/10	21.43	09/27/10	608	10/03/11	2.890	244	06/03/12	1.630	583	01/07/14	1435	3.93
1982 DV	04/26/00	39.73	09/28/01	818	07/23/02	1.547	286	05/05/03	0.643	724	04/27/05	1828	5.00
	05/01/06	35.20	07/01/07	710	04/10/08	2.032	120	08/08/08	2.529	622	04/22/10	1452	3.97
	05/01/09	32.08	06/13/10	681	03/14/11	2.315	120	07/12/11	2.230	651	04/22/13	1452	3.98
433 Eros	01/23/91	36.31	11/19/91	609	09/23/92	1.403	90	12/22/92	2.115	396	01/22/94	1095	3.00
	01/20/93	28.17	10/25/93	524	06/28/94	2.553	201	01/15/95	1.007	375	01/24/96	1100	3.01
	01/21/00	29.66	10/29/00	540	07/14/01	2.319	165	12/26/01	1.172	394	01/24/03	1099	3.01
	01/21/07	31.17	11/03/07	555	07/29/08	2.096	141	12/17/08	1.357	403	01/24/10	1099	3.01

inclusion in this paper. Tables 15 and 16 list the results of both searches. The stay time at the asteroid varies from 30 to 352 days, and the length of the entire sample return mission ranges from 1.29 to 5.96 years.

Conclusion

We have shown in this paper that the global minimum total ΔV is a viable measure of accessibility. We have extensively tested and demonstrated that asteroids ranked high actually had more mission opportunities requiring less total ΔV than those ranked low. We have also demonstrated a good correlation between our ranking and the ΔV-weighted frequency of opportunities. In addition, many new ballistic rendezvous and sample return missions for some selected near-Earth asteroids with launch dates from 1990 to 2010 were identified with the aid of this ranking. These two lists of feasible opportunities can be used as a guide in the selection of near-Earth asteroids for future missions.

An attempt to generate a good rule of thumb for statistically computing the global minimum total ΔV as a function of eccentricity, inclination, and perihelion distance was unsuccessful. Nevertheless, the existing method for determining this number is sufficiently straightforward and quick to be readily computed for each new discovery after its orbital elements have been fixed.

Addendum

After the final draft of this paper was completed for publication, it was learned that six near-Earth asteroids were discovered[20] between Feb. 6, 1985 and June 13, 1986, thus raising the total of known near-Earth asteroids to eighty-eight. These are: 1985 PA, 1985 TB, 1985 WA, 1986 DA, 1986 EB, and 1986 LA. The orbital elements for these asteroids are not certain, but preliminary assessment indicates that they are not good mission candidates, with the exception of 1986 LA. This most recently discovered minor planet has a global minimum total ΔV of a little over 6 km/s, thus making it one of the top fifteen most accessible near-Earth asteroids.

Acknowledgments

The authors would like to thank Drs. D.F. Bender and A.H. Cutler, E.F. Helin, K.T. Nock, and C.G. Sauer for useful discussions and contributions of ideas. The trajectory optimizer used to find real opportunities at the global minimum total ΔV was designed by Carl Sauer. Helen Ling generated all of the plots, and LaVera Farnsworth typed the manuscript. The work described in this paper was carried out in part by the Jet Propulsion Laboratory, California Institute of Technology, under Contract NAS7-918 with the National Aeronautics and Space Administration.

References

[1] "Report of the Terrestrial Bodies Science Working Group" Vol. 6, The Asteroids, JPL Publications 77-51, 1977.

[2] "Asteroids," *Strategy for the Exploration of Primitive Solar System Bodies—Asteroids, Comets and Meteroroids,* Committee on Planetary and Lunar Exploration, National Academy of Sciences, 1980, pp. 40–53.

[3] O'Leary, B., "Asteroid Mining," *Astronomy,* Vol. 6, 1978, pp. 6–15.

[4] Herrick, S., "Exploration and 1994 Exploitation of Geographos," *Asteroids,* edited by T. Gehrels, University of Arizona Press, Tucson, AZ, 1979, pp. 222–226.

[5] Steurer, W.N., *Extraterrestrial Material Processing,* JPL Publication 82-42, 1982.

[6] Arnold, J.R. and Duke, M., *NASA Summer Workshop on Near-Earth Resources,* NASA Conference Publication 2031, 1978.

[7] French, J.R. Jr. and Hulkower, N.D., "Exploration of the Asteroids," JBIS 35, 1982, pp. 167–171.

[8] Hulkower, N.D., Lau, C.O., and Bender, D. F., "Optimum Two-Impulse Transfer for Preliminary Interplanetary Trajectory Design," *Journal of Guidance,* Vol 7, 1984, pp. 458–461.

[9] Helin, E.F., Hulkower, N.D., and Bender, D.F., "The Discovery of 1982 DB, the Most Accessible Asteroid Known," *Icarus,* Vol. 57, 1984, pp. 42–47; erratum in Vol. 59, 1984, p. 132.

[10] Helin, E.F., "Earth-Crossing Asteroids: New Discoveries," *Sun and Planetary System,* edited by W. Fricke and G. Teleki, 1982, pp. 269–276.

[11] Helin, E.F. and Dunbar, R.S., private communication, 1985.

[12] Gradie, J. and Tedesco, T., "Compositional Structure of the Asteroid Belt," *Science,* Vol. 216, 1982, pp. 1405–1407.

[13] Hulkower, N.D. and Ross D.J., " Missions to the Asteroid Anteros and the Space of True Anomalies," *Acta Astronautica,* Vol. 10, 1983, pp. 133–141.

[14] Stancati, M.L. and Soldner, J.K., "Near-Earth Asteroids: A Survey of Ballistic Rendezvous and Sample Return Missions," AAS Paper 81-185, 1981.

[15] Wallace, R.A., Blume, W.H., Hulkower, N.D., and Yen, C.L., "Interplanetary Missions for the Late Twentieth Century," *Journal of Spacecraft,* Vol. 22, 1985, pp. 316–324.

[16] Yen, C.L., "Mission Opportunity Maps for Rendezvous with Earth-Crossing Asteroids," AIAA 84-2029, 1984.

[17] Bender, D.F., to be published in the NEAR Study Report, 1985.

[18] Niehoff, J.C., "Round-trip Mission Requirements for Asteroids 1976 AA and 1973 EC," *Icarus,* Vol 31, pp. 430–438.

[19] Friedlander, A., "Short Round Trip Opportunities to Asteroid 1982 DB During the Close Approach in 2001-02," SAI Memo to Rick Pomphrey, 1982.

[20] Helin, E.F., private communication, 1986.