NEA SR TRS: MISSION ANALYSIS ANNEX

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1 CHEMICAL OUTBOUND MISSIONS

The ΔV margin philosophy is available in [Atzei07]. The selected targets for which mission analysis was performed are listed in [Agnolon07]. All transfers depart from GTO (therefore independent of launch vehicle performances). Some deep space manoeuvres are executed primarily to phase the trajectory, and to perform minor changes of the semi-major axis, eccentricity or inclination. At arrival to the target, a rendezvous manoeuvre has to be performed in order to capture with the asteroid orbits (cancel out the spacecraft V_{inf} relative to the target). Only transfers performing less than 2 complete heliocentric revolutions around the sun have been taken into account to reduce mission duration and therefore operations cost.

1.1 Chemical transfer to 1999JU3

Table 1 summarises the best subset of chemical outbound opportunities to 1999JU3 in the 2015-2025 timeframe.

Table 1: Summary of chemical transfers opportunities to 1999JU3

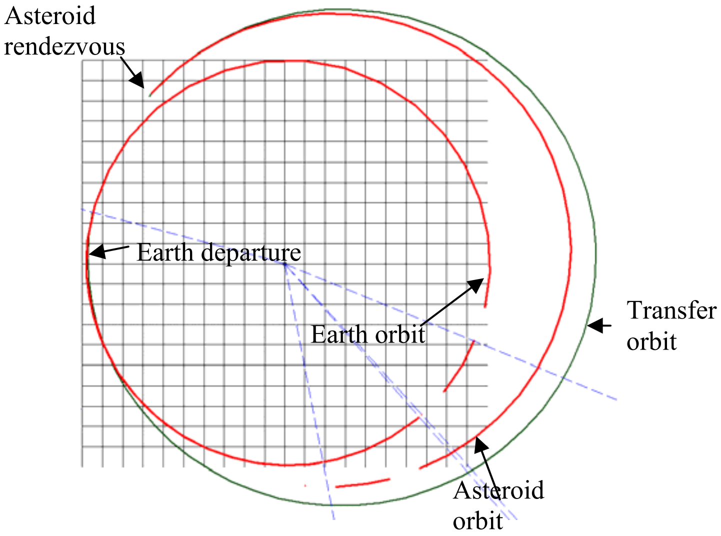
launch (dd/mm/yyyy)	arrival (dd/mm/yyyy)	**transfer time (days)**	dep v_inf (m/s)	launch incl (deg)	ΔV_dep (m/s)	ΔV_mcc (m/s)	arr v_inf (m/s)	ΔV from GTO (m/s)	**ΔV from GTO with margin (m/s)**
04/12/2015	30/04/2018	**866**	4139.2	-58.8	2167.1	0.0	614.5	2167.1	**2275.47**
05/12/2016	11/07/2019	**936**	4385.1	-50.9	2027.5	28.0	384.9	2055.5	**2158.31**
03/12/2020	11/02/2022	**428**	4560.6	-54.3	1740.9	5.0	31.7	1745.9	**1833.22**
03/12/2020	04/05/2023	**871**	4562.5	-54.4	1727.8	17.0	17.2	1744.8	**1832.03**
03/12/2024	28/05/2027	**895**	4328.8	-56.8	1965.2	1.0	344.4	1966.2	**2064.49**

Launcher dispersion correction is not taken into account. Typically such a manoeuvre is performed 2 days after launch (after performing tracking) and requires 30 m/s with Soyuz. The table shows a number of transfers requiring around 2 km/s. On average the transfer time is ~ 2.5 years, except one of the 2020 opportunities. It is important to notice that all transfers start off with a significant launch inclination, 50^o at least, which causes a penalty with Soyuz from Kourou.
Solutions to overcome this issue are:

- To perform a plane change manoeuvre near the apocentre of a highly elliptical orbit which typically requires 200-300m/s ΔV for a required 50^o declination
- To first leave the Earth and perform an Earth Gravity Assist manoeuvre in order to achieve the desired inclination without any ΔV penalties but with a transfer time penalty of 1 year

The plot below represents a typical transfer to 1999JU3, specifically the 2016 transfer opportunity.

Figure 1: 2016 chemical transfer to 1999JU3. Earth and asteroid orbits in red; transfer trajectory in green



1.2 *Chemical transfers to Nereus*

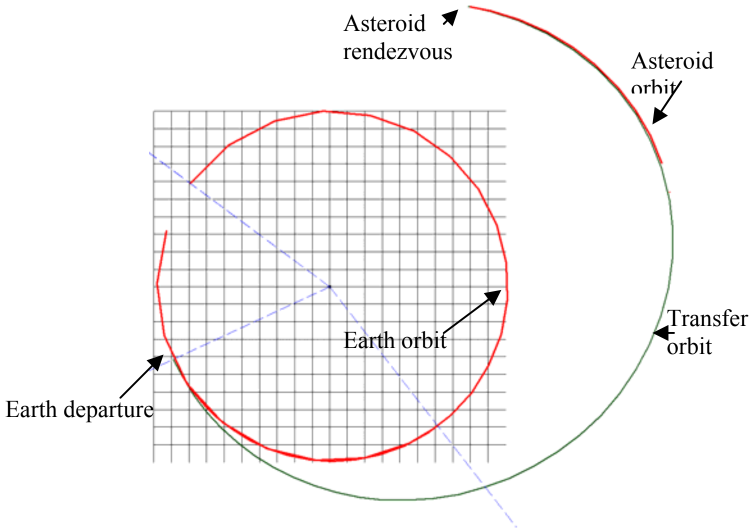
The same analysis performed for 1999JU3 has been applied to Nereus and the other pre-selected targets. Table 2 shows the best opportunities with a ΔV lower than 2.5 km/s.

Table 2: Summary of chemical transfers to Nereus

launch (dd/mm/yyyy)	arrival (dd/mm/yyyy)	**transfer time (days)**	dep v_inf (m/s)	ΔV_dep (m/s)	launch incl (deg)	ΔV_mcc (m/s)	arr v_inf (m/s)	ΔV from GTO (m/s)	**ΔV from GTO with margins (m/s)**
26/01/2015	07/05/2018	1181	4399.0	1647.4	-19.5	199.0	490.4	2336.8	**2453.6**
12/01/2020	10/07/2023	1258	4827.6	1817.4	-13.6	0.0	457.7	2275.0	**2388.8**
15/01/2022	28/04/2023	463	4550.1	1705.5	-13.5	0.0	457.0	2162.4	**2270.5**
22/01/2022	25/06/2025	1233	4781.8	1797.3	-18.6	237.0	22.7	2057.0	**2159.9**
24/01/2024	15/06/2027	1221	4517.5	1693.1	-19.3	226.0	315.6	2234.7	**2346.4**

The table shows that transfers to Nereus are a bit more demanding in terms of ΔV than transfers to 1999JU3. The required launch inclination is always lower than 20 degrees which does not require any significant ΔV with Soyuz from Kourou. Transfer time is around 3.3 years except for one of the 2022 opportunities. The plot below presents the short 2022 transfer trajectory to Nereus.

Figure 2: 2022 transfer opportunity to Nereus



1.3 Chemical transfers to 1996FG3

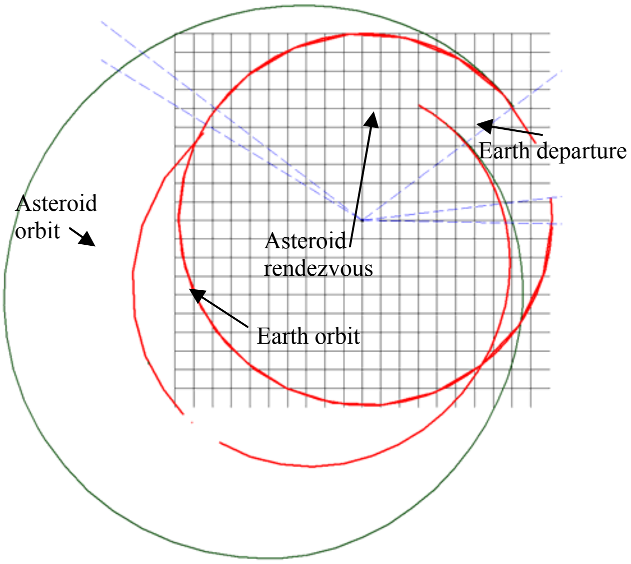
Table 3: Summary of chemical transfers to 1996 FG3

launch (dd/mm/yyyy)	arrival (dd/mm/yyyy)	**transfer time (days)**	dep v_inf (m/s)	dep incl (deg)	ΔV_dep (m/s)	ΔV_mcc (m/s)	arr v_inf (m/s)	ΔV from GTO (m/s)	**ΔV from GTO with margins (m/s)**
24/07/2015	13/09/2017	769	2968.5	39.8	1185.8	1981.0	679.1	3845.9	**4038.20**
21/01/2018	15/04/2019	444	3818.3	6.3	1440.5	0.0	2603.0	4043.5	**4245.66**
22/01/2019	17/05/2020	475	3603.7	3.8	1370.2	999.0	1663.8	4033.0	**4234.67**
23/07/2025	15/05/2026	292	2938.9	38.3	1178.0	816.0	1875.6	3869.6	**4063.03**

It is to be noticed that 1996FG3 is the most accessible real C-type asteroid (1999JU3 being of Cg type). The transfer times span from 10 months up to 2.1 year. Required departure declination varies in the range [4-40]°. All transfers require a large rendezvous manoeuvre or substantial deep space manoeuvre or both, which make the overall mission ΔV about twice as large as in the 1999JU3 and Nereus cases. These ΔV values make a chemical mission very unlikely. Yet, the preliminary model (based on a simplified Hohmann transfer [Agnolon07]) showed similar outbound ΔV as for 1999JU3 and Nereus. The reasons why the transfers now turn out to be more demanding than for 1999JU3 and Nereus mainly are:

- Earth's orbit and the asteroid orbit are intersecting, and intersection happens with a significant crossing velocity
- The semimajor axis of this asteroid is very close to 1AU which means that the initial bad phasing with Earth at the beginning of the launch window does not improve over the considered launch window of 10 years and translates into a large deep space manoeuvre

Figure 3: 2019 opportunity to 1996FG3



The transfer trajectory goes out to about 2AU even though the asteroid's aphelion is 1.4 AU, making the transfer quite demanding. Subsequently, the perihelion has then to be lowered to about 0.7 AU. This is clearly an effect of bad phasing between Earth and asteroid.

1.4 Chemical transfers to 1998QA1, 1998KU2 and 4015 Wilson-Harrington

These three targets are very similar in terms of ephemeris, thus have a similar accessibility. The high aphelions to be reached make transfers to these asteroids typically very long, so only trajectories performing less than 1 heliocentric revolution have been considered.

Table 4: Chemical transfer to 1998QA1

launch (dd/mm/yyyy)	arrival (dd/mm/yyyy)	**transfer time (days)**	dep v_inf (m/s)	dep incl (deg)	ΔV_dep (m/s)	ΔV_mcc (m/s)	arr v_inf (m/s)	ΔV from GTO (m/s)	**ΔV from GTO with margins (m/s)**
24/06/2016	17/04/2019	1013	7971.1	16.9	3413.2	0.0	1531.1	**4944.2**	**5191.45**
15/07/2017	05/10/2019	800	7660.2	28.1	3231.2	528.0	1167.3	**4926.5**	**5172.80**
24/06/2019	14/05/2022	1040	8057.7	17.5	3464.9	0.0	1590.8	**5055.7**	**5308.52**
24/06/2022	11/06/2025	1067	8146.2	18.0	3518.1	0.0	1648.6	**5166.7**	**5424.99**
18/07/2023	10/11/2025	832	8533.5	31.2	3756.0	148.0	967.0	**4871.0**	**5114.58**
14/07/2026	21/11/2028	847	7865.6	26.4	3350.8	547.4	904.6	**4802.8**	**5042.92**

Table 5: Chemical transfer to 1998KU2

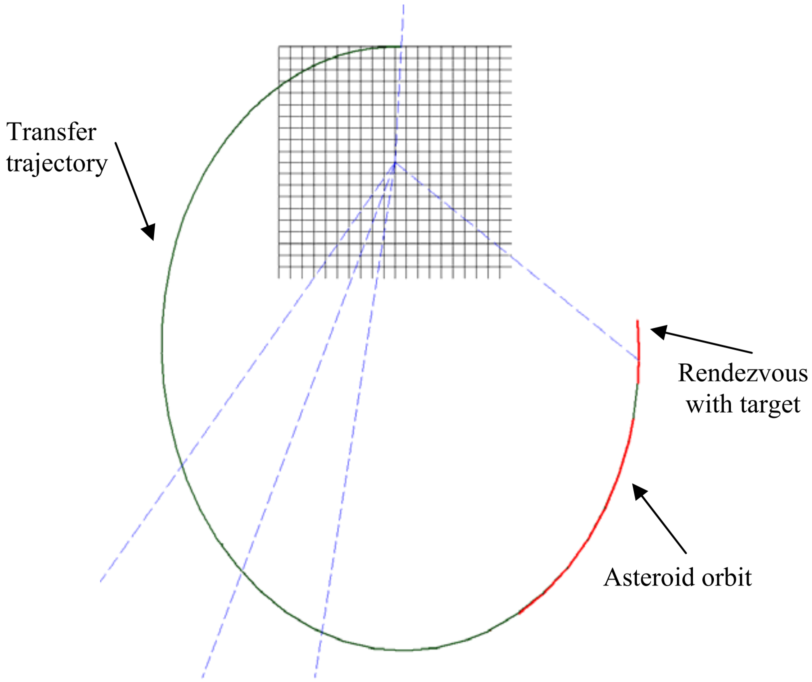
launch (dd/mm/yyyy)	arrival (dd/mm/yyyy)	**transfer time (days)**	dep v_inf (m/s)	dep incl (deg)	ΔV_dep (m/s)	ΔV_mcc (m/s)	arr v_inf (m/s)	ΔV from GTO (m/s)	**ΔV from GTO with margins (m/s)**
17/08/2015	31/05/2018	1004	7396.1	20.4	3079.6	0.0	1478.9	**4558.5**	**4786.41**
14/08/2018	02/11/2021	1158	7759.1	17.6	3288.5	0.0	1664.6	**4953.1**	**5200.76**
02/09/2019	27/01/2022	865	6985.0	3.4	2850.9	204.4	1882.3	**4937.6**	**5184.44**
21/08/2022	08/04/2025	947	7134.5	16.4	2933.2	0.0	1683.4	**4616.6**	**4847.43**
17/09/2023	10/08/2025	683	6605.6	-7.7	2649.5	226.0	2614.1	**5489.7**	**5764.14**
15/08/2025	19/07/2028	1054	7541.9	20.4	3162.6	0.0	1486.5	**4649.1**	**4881.52**

Table 6: Chemical transfer to Wilson-Harrington

launch (dd/mm/yyyy)	arrival (dd/mm/yyyy)	**transfer time (days)**	dep v_inf (m/s)	dep incl (deg)	ΔV_dep (m/s)	ΔV_mcc (m/s)	arr v_inf (m/s)	ΔV from GTO (m/s)	**ΔV from GTO with margins (m/s)**
23/09/2015	08/05/2018	945	6473.8	27.1	2579.9	1102.0	1568.7	**5250.5**	**5513.05**
22/09/2018	21/03/2022	1259	7935.9	28.0	3393.3	0.0	1133.4	**4526.6**	**4752.95**
05/10/2019	08/07/2022	993	7045.1	12.8	2884.1	389.0	1823.4	**5096.5**	**5351.37**
19/09/2022	11/05/2026	1312	8207.9	31.2	3555.4	0.0	868.0	**4423.4**	**4644.55**
03/10/2023	05/10/2026	1082	7334.6	15.1	3045.6	346.0	1526.4	**4918.0**	**5163.89**
19/09/2026	04/09/2030	1425	8372.8	30.3	3656.2	731.0	172.6	**4559.7**	**4787.73**

Transfer times are rather long, around 3 years. ΔV are all ~ 5km/s, which is far beyond the range of a Soyuz chemical transfer for the envisaged mission. This is partly due to the rendezvous manoeuvre with the asteroid, but mainly due to the very high required Earth escape velocity. The plot below shows a typical transfer to Wilson-Harrington.

Figure 4: 2022 opportunity to Wilson-Harrington



An interesting option for reducing such ΔVs lies in the utilisation of gravity assist manoeuvres. Such missions would typically use Venus-Earth (VE) or Venus-Earth-Earth (VEE) sequences. The table below shows a summary of such missions to Wilson-Harrington. Forward transfer time is still quite long (minimum 4.5 years).

Table 7: Chemical transfers to Wilson Harrington with gravity assists

launch (dd/mm/yyyy)	arrival (dd/mm/yyyy)	dep v_inf (m/s)	dep incl (deg)	dv_dep (m/s)	dv_mcc (m/s)	arr v_inf (m/s)	**dv from GTO (m/s) with margin**	Flyby sequence
04/03/2017	28/09/2024	3944.03	26.87	1483.13	571.03	168.63	2333.93	VEE
24/01/2017	25/10/2023	3766.31	39.06	1423.22	1.19	618.90	2145.48	VEE
23/03/2018	30/12/2023	3211.17	31.47	1252.13	354.90	643.16	2362.70	VE
04/04/2018	03/07/2024	3672.25	1.18	1392.51	524.77	268.78	2295.36	VE
16/04/2020	16/11/2024	3315.45	14.09	1282.38	564.97	1053.58	3045.97	VE
10/05/2021	19/05/2028	3578.64	53.76	1362.63	1062.12	250.32	2808.83	VE
27/05/2023	20/10/2028	3174.84	48.04	1241.80	740.35	907.23	3033.85	VE

1.5 *Chemical transfers to 2002AT4*

The taxonomy type of 2002AT4 is uncertain. It could be a D-type. For this reason it is only suitable for an in-situ only mission concept in the frame of this study. Only transfer with a lower ΔV than 3.1 km/s are shown.

Table 8: Chemical transfers to 2002AT4

launch (dd/mm/yyyy)	arrival (dd/mm/yyyy)	**transfer time (days)**	dep v_inf (m/s)	ΔV_dep (m/s)	launch incl (deg)	ΔV_mcc (m/s)	arr v_inf (m/s)	ΔV from GTO (m/s)	**ΔV from GTO with margins (m/s)**
03/03/2015	27/10/2017	**954**	5779.7	2236.6	-30.0	163.0	522.5	2922.1	**3068.24**
11/03/2020	19/03/2022	**728**	6006.2	2345.5	-32.2	0.0	535.1	2880.7	**3024.69**
02/03/2020	15/12/2022	**1003**	5976.0	2330.8	-29.6	0.0	485.3	2816.1	**2956.91**
07/03/2025	08/05/2027	**781**	6249.1	2465.7	-34.4	358.9	1.0	2825.5	**2966.83**
05/03/2025	19/04/2028	**1124**	6111.2	2396.7	-27.3	99.0	253.2	2748.9	**2886.32**

ΔV is in the range 3 km/s for the best opportunities which is quite higher than for 1999JU3 and Nereus but it might remain accessible to a chemically-propelled spacecraft launched by Soyuz.

2 CHEMICAL RETURN MISSIONS

2.1 *Return opportunities*

In the analysis of chemical return trajectories only transfers performing less than 1 heliocentric revolution have been considered to minimize operational costs. Due to the small gravitational field of asteroids, all the given departure ΔVs translate into $V_{inf\_asteroid}$. At arrival at Earth, no capture manoeuvre is performed: the probe experiences direct re-entry. The resulting atmospheric entry velocity should be below 12.5km/s due to engineering constraints [Agnolon07]. It is to be noted that the departure is assumed to occur with no relative velocity with respect to the asteroid. ΔVs to manoeuvre within the asteroid vicinity or from the surface to orbit are negligible with respect to the total ΔV in most cases.

2.1.1 CHEMICAL RETURN TRAJECTORIES FROM 1999JU3

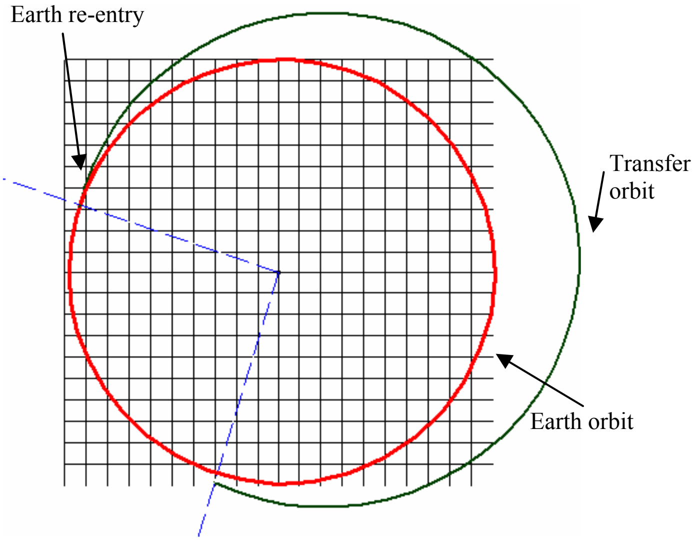
Best return opportunities (ΔV lower than 2 km/s) are shown in Table 9.

Table 9: Chemical return transfers from 1999JU3

departure dd/mm/yyyy	arrival dd/mm/yyyy	**transfer time (days)**	dep v_inf (m/s)	ΔV_mcc (m/s)	arr v_inf (m/s)	ΔV total (m/s)	v atmosph. (m/s)	ΔV with margin (m/s)
13/05/2018	05/12/2019	**562**	1420.3	8.0	5709.0	1428.3	12476.2	**1499.7**
11/11/2019	04/12/2020	**383**	6.9	0.0	4579.0	6.9	12001.3	**7.2**
03/04/2022	05/12/2023	**602**	1831.8	10.0	6054.1	1841.8	12637.8	**1933.9**
20/07/2023	04/12/2024	**494**	588.0	5.0	5030.4	593.0	12180.6	**622.7**
04/11/2024	04/12/2025	**390**	1270.7	0.0	3832.3	1270.7	11736.7	**1334.2**

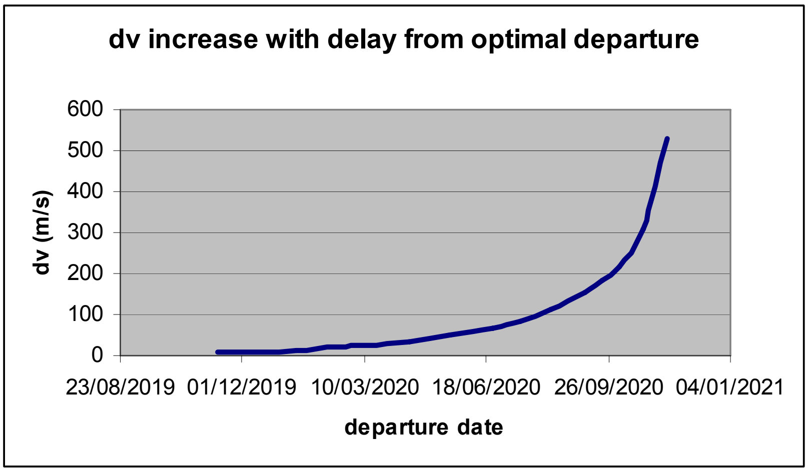
Return trajectories take between 1 and 2 years. ΔVs can be very different and highly sensitive to the transfer epoch. Two very good opportunities occur in 2019 and 2023 with a return ΔV lower than 600 m/s without any margin. This is due to the fact that the asteroid passes by relatively close to the Earth around these given dates (~10 times the distance Earth-Moon in Dec. 2020). An important fact is that the arrival atmospheric entry velocity is nearly always within the specified limit of 12.5km/s, even though this parameter has not been explicitly constrained. The 2019 transfer is presented on the plot below. The asteroid orbit is almost coincident with the transfer trajectory and is not shown.

Figure 5: 2019 return opportunity from 1999JU3



More analysis has been performed on this particular solution, in order to assess what is the impact of a delayed departure on the trajectory ΔV. The result of this analysis is summarised in the table below. The departure can be easily delayed by several months with almost no ΔV penalty. For instance, delaying the departure by 8 months would still provide a transfer with ΔV requirement below 100 m/s.

Figure 6: 2019 return opportunity from 1999JU3. ΔV evolution with a delayed departure



2.1.2 CHEMICAL RETURN TRAJECTORIES FROM NEREUS

Best return opportunities (ΔV lower than 1 km/s) are shown here after.

Table 10: Chemical return transfers from Nereus

departure dd/mm/yyyy	arrival dd/mm/yyyy	**transfer time (days)**	dep v_inf (m/s)	ΔV_mcc (m/s)	arr v_inf (m/s)	ΔV total (m/s)	v atmosph. (m/s)	**ΔV with margin (m/s)**
13/05/2018	16/02/2020	**633**	609.5	0.0	5533.4	609.5	12396.8	**640.0**
06/09/2020	09/02/2022	**513**	81.1	0.0	5765.6	81.1	12502.2	**85.2**
08/03/2022	10/02/2024	**692**	620.1	0.0	6046.2	620.1	12634.1	**651.1**
20/06/2027	16/02/2029	**596**	949.6	0.0	5149.6	949.6	12230.3	**997.0**

None of the transfers presented performs a DSM, and none of these transfers has an atmospheric entry velocity above the targeted limit of 12.5 km/s. The best transfer only requires 85 m/s, and, as in the previous case, there is the possibility to anticipate or delay the departure from the asteroid by several months without any substantial penalty on the ΔV. Interestingly, it is possible to find trajectories requiring less than 650 m/s over the first 4 years.

2.1.3 CHEMICAL RETURN TRAJECTORIES FROM 1996FG3

Best return opportunities (ΔV lower than 1.1 km/s) are shown here after.

Table 11: Chemical return transfers from 1996FG3

departure dd/mm/yyyy	arrival dd/mm/yyyy	**transfer time (days)**	dep v_inf (m/s)	dv_mcc (m/s)	arr v_inf (m/s)	dv total (m/s)	v atmosph. (m/s)	**dv with margin (m/s)**
10/05/2020	05/05/2021	**355**	456.2	557.2	11732.4	1013.4	16146.6	**1064.1**
03/11/2021	26/04/2022	**173**	827.2	0.0	11284.0	827.2	15823.8	**868.5**
16/08/2023	24/11/2024	**458**	91.9	607.0	10809.2	698.9	15488.7	**733.8**
13/03/2025	03/12/2025	**260**	931.0	0.0	12448.8	931.0	16674.4	**977.5**

Transfer times are quite short (0.5<T<1.3 years). The return ΔVs are also reasonably low, even though slightly higher than for the 2 previous cases. But most importantly the V_{inf_Earth} is very high and leads to a prohibitive Earth re-entry speed (at 100 km altitude) never lower than 15.5 km/s. Different ways exist for lowering V_{inf_Earth}, but all of them obviously have drawbacks:

- Performing an EGA manoeuvre at the nominal arrival date and then coming back to Earth typically about 12 months later with a reduced V_{inf_Earth}. The main drawback of this solution is the extended duration of the transfer.
- Alternatively, constraining the arrival V_{inf_Earth} so that V_{atm}<12.5 km/s. The ΔV penalty for the 2023 trajectory for instance is ~ 2 km/s, which is not realistic for a chemical mission.

These results confirm the difficulty of a target such as 1996 FG3. A Soyuz chemical sample return is very likely not feasible as confirmed by preliminary launch mass budget [Agnolon07].

2.1.4 CHEMICAL RETURNS FROM 1998QA1, 1998KU2, 4015 WILSON-HARRINGTON

Due to the high aphelions of these targets, leaving V_{inf_Earth} unconstrained would present very high V_{atm}, typically around 17 km/s, which is not desired. V_{inf_Earth} therefore has to be constrained so that the atmospheric velocity remains below 12.5 km/s. All transfers have a minimum total ΔV of 2.3 km/s. Wilson-Harrington transfers only are presented since it has the best opportunity of all but the other targets have similar results (2.5<ΔV<2.9 km/s).

Table 12: Return transfers from Wilson-Harrington

departure dd/mm/yyyy	arrival dd/mm/yyyy	**transfer time (days)**	dep v_inf (m/s)	ΔV_mcc (m/s)	arr v_inf (m/s)	ΔV total (m/s)	ΔV capture (m/s)	total ΔV (m/s)	atmosph. entry (m/s)	**ΔV with margin (m/s)**
23/07/2014	27/09/2018	1504	661.7	378.0	8327.9	1039.7	1385.3	2425.0	12500.0	**2546.2**
12/07/2018	14/09/2021	1142	1115.0	564.0	7511.5	1679.0	906.6	2585.5	12500.0	**2714.8**
12/01/2019	25/09/2022	1333	364.9	546.0	8151.5	910.9	1279.1	2190.1	12500.0	**2299.6**
10/02/2023	21/09/2026	1301	533.9	498.0	8014.2	1031.9	1197.5	2229.4	12500.0	**2340.9**
20/01/2027	10/09/2029	950	1854.7	522.0	6893.9	2376.7	566.9	2943.6	12500.0	**3090.8**

Transfer times are always very long, in the range [2.6-4] years which obviously lead to longer mission operations and cost. The optimal solution from a ΔV point of view always is a strategy where the targeted V_{atm} of 12.5 km/s at ~ 100 km altitude is reached by a combination of ΔV spent to modify the transfer and ΔV spent in a capture manoeuvre within Earth's sphere of influence. This last manoeuvre is only possible with a chemical system onboard, and it is not a very good strategy from a mission safety point of view. This makes these targets unlikely for a sample return mission with chemical propulsion. A possible way to improve the situation again lies in performing an EGA and come back to Earth a year later with a reduced V_{inf_Earth} with its associated drawbacks.

2.2 *Identified roundtrip opportunities*

Based on the results presented so far, it is possible to identify some roundtrip missions to be performed with chemical systems. In all cases the stay time at the asteroid is bound to be at least 3 months. The opportunities are divided into mission classes with return transfer ΔV below 300m/s, around 600m/s and around 1000m/s. As shown before, the only possible targets for a fully chemical cost and mass-efficient design are 1999JU3 or Nereus (however more constrained than JU3), due to their much better accessibility, both outbound and inbound.

The summary of the best opportunities is presented here below.

- Low class return ΔV missions: up to 300m/s

Table 13: Low return-ΔV transfers

Target	launch dd/mm/yyyy	**arrival dd/mm/yyyy**	ΔV from GTO (m/s)	**Return dd/mm/yyyy**	arrival dd/mm/yyyy	ΔV_return m/s	v_entry m/s	ΔV_total (m/s)	**ΔV with margin (m/s)**
1999ju3	05/12/2016	**11/07/2019**	2055.5	**11/11/2019**	04/12/2020	6.9	12001.3	2062.4	**2165.6**
Nereus	26/01/2017	**10/03/2020**	2548.2	**06/09/2020**	09/02/2022	81.1	12502.2	2629.3	**2760.8**
1999ju3	08/12/2017	**01/08/2019**	3921.6	**11/11/2019**	04/12/2020	6.9	12001.3	3928.5	**4124.9**

- Middle class return ΔV missions: up to 600m/s

Table 14: Middle return-ΔV transfers

Target	launch dd/mm/yyyy	**arrival dd/mm/yyyy**	ΔV from GTO (m/s)	**Return dd/mm/yyyy**	arrival dd/mm/yyyy	ΔV_return m/s	v_entry m/s	ΔV_total (m/s)	**ΔV with margin (m/s)**
Nereus	26/01/2015	**07/05/2018**	2336.8	**13/05/2018**	16/02/2020	609.5	12396.0	2946.3	**3093.6**
Nereus	10/01/2020	**19/10/2021**	2642.9	**08/03/2022**	10/02/2024	620.1	12634.1	3263.0	**3426.1**
1999ju3	03/12/2020	**11/02/2022**	1745.9	**20/07/2023**	04/12/2024	593.0	12180.6	2338.9	**2455.9**
1999ju3	03/12/2020	**04/05/2023**	1744.8	**20/07/2023**	04/12/2024	593.0	12180.6	2337.8	**2454.7**

- High class return ΔV mission: around 1000m/s

Table 15: High return-ΔV transfers

Target	launch dd/mm/yyyy	**arrival dd/mm/yyyy**	ΔV from GTO (m/s)	**Return dd/mm/yyyy**	arrival dd/mm/yyyy	ΔV_return m/s	v_entry m/s	ΔV_total (m/s)	**ΔV with margin (m/s)**
1999ju3	03/12/2020	**04/05/2023**	1744.8	**04/11/2024**	04/12/2025	1271.0	11736.0	3015.8	**3166.6**
Nereus	15/01/2022	**28/04/2023**	2162.4	**29/10/2023**	08/02/2026	986.0	13141.0	3148.4	**3305.8**
Nereus	24/01/2024	**15/06/2027**	2234.7	**20/06/2027**	16/02/2029	950.0	12230.0	3184.7	**3343.9**

3 SEP TRANSFERS

3.1 SEP departure strategy

The results for chemical transfers to asteroids show that the required ΔV is quite often too high for most targets in order to undertake a mission with a sufficiently high dry mass. Solar Electric Propulsion, due to its much higher Isp, can greatly reduced the amount of fuel required. However, it has major drawbacks which one has to bear in mind: cost, transfer duration and power demand. The engineering consequences of the high power demand are assessed in NEA-SR TRS study overview.
Converting the previous chemical transfers to SEP transfers means spreading out in time the impulsive chemical manoeuvres which typically results in a higher ΔV due to gravity losses and also because the manoeuvre does not occur at the optimal place. Nevertheless, most of the transfers presented so far have quite low DSM, so this negative effect is limited.

One of the most efficient injection strategies for an interplanetary SEP is the following sequence:

1. Launch into GTO
2. Raise apogee to lunar crossing orbit by chemical propulsion stage (which requires ~ 700 m/s from GTO)

3. Perform a Lunar Gravity Assist (typically a V_{inf_Earth} of 1100 m/s is achievable)
4. Leave Earth and thrust for increasing eccentricity of heliocentric orbit and for targeting Earth
5. Come back to Earth after typically 15 months and perform Earth Gravity assist to achieve required V_{inf_Earth}
6. When high departure V_{inf_Earth} is looked for and the available thrust is very low, it is necessary to perform one extra heliocentric revolution, extending this phase of the mission to typically 27 months

A slightly less performing scenario is to launch the spacecraft into Lunar Crossing Orbit directly through Fregat and then perform steps 3-4-5-6 as for the previous strategy. The LGA allows about 130 m/s savings to the ΔV to be provided by the chemical propulsion system. Several thrust-to-mass ratios have been considered in order to find the impact of the thrust level on the transfer ΔV. The optimal thrust is determined at system level, by taking into account the mass of the propulsion system, the power system, etc. All SEP transfers presented assume LGA-EGA sequence at the beginning of the mission.

3.2 SEP outbound and chemical return

3.2.1 LOW RETURN ΔV CLASS MISSIONS TO 1999JU3 WITH SEP

The optimal roundtrip mission to 1999 JU3 presented in Table 13 has been converted to an analogous low thrust transfers for the outbound leg, with the addition of the LGA-EGA sequence at the beginning of the transfer that shifts the launch date back in time of 15 months compared to the chemical case. The return transfer is chemical. The transfer has been re-optimised with several thrust levels. The thrust model used here assumes constant thrust regardless to the distance from the sun (this is obviously not a realistic case and the mission design has to account for power variation versus Sun-distance if SEP is baselined). A sample of the results for different thrusts level is shown below.

Table 16: 2015 SEP outbound transfers to 1999JU3

thrust/mass (mN/t)	launch dd/mm/yyy	**arrival dd/mm/yyyy**	transfer time days	chem ΔV m/s	SEP ΔV m/s	**SEP ΔV with margin m/s**
500	03/10/2015	**17/06/2019**	1334	700	1727.47	**1796.57**
300	02/10/2015	**18/06/2019**	1336	700	1734.22	**1803.59**
200	02/10/2015	**19/06/2019**	1337	700	1746.26	**1816.11**
150	01/10/2015	**22/06/2019**	1341	700	1765.49	**1836.11**
100	30/09/2015	**01/07/2019**	1351	700	1828.76	**1901.91**
75	27/09/2015	**11/07/2019**	1364	700	1952.37	**2030.47**
60	14/10/2015	**20/07/2019**	1356	700	2138.01	**2223.53**
50	19/10/2015	**03/08/2019**	1364	700	2248.31	**2338.24**

Results show, as expected, a ΔV increase when the thrust decreases. The increase is ~ 20/25% for the lowest thrust if compared to the impulsive transfer. This means that it is very likely that a SEP transfer would give a consistent mass advantage compared to the chemical one. The other effect of SEP on the transfer is a delay of the optimal arrival date at the asteroid with the decrease of the thrust level. There is about 1.5 month difference between the impulsive transfer and the 50mN/tonne transfer. This is not an issue, as the optimal departure date for the return leg (November 2019) can be delayed by several months with no penalty.

The graph below shows the ΔV increase with respect to thrust used for this transfer. There is an exponential growth in ΔV when the thrust-to-mass ratio goes below about 100mN/tonne

Figure 7: ΔV as a function of thrust for 2015 SEP transfer to 1999JU3

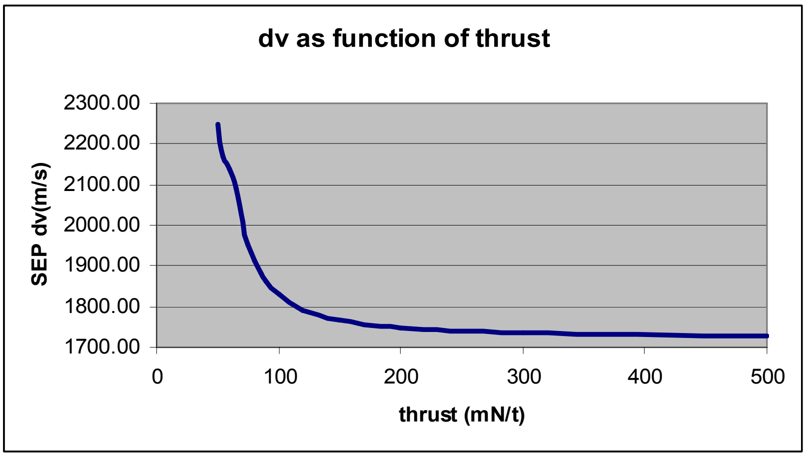
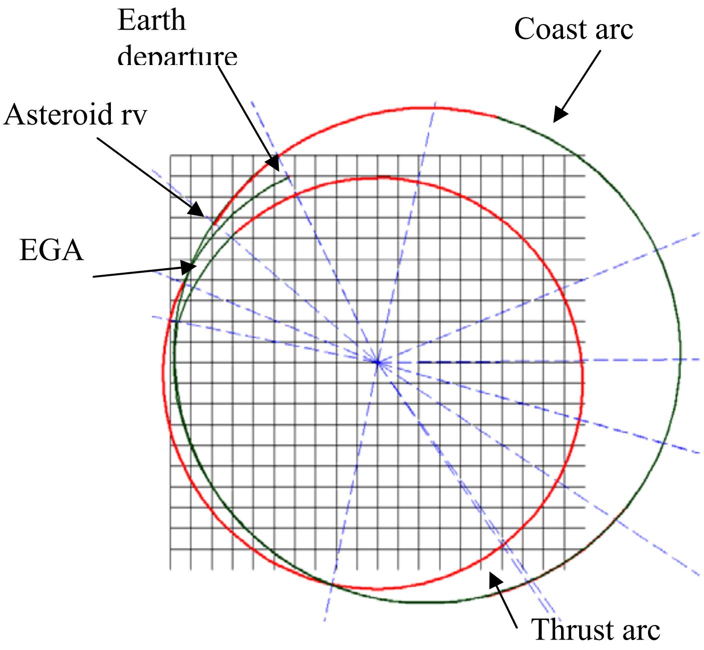


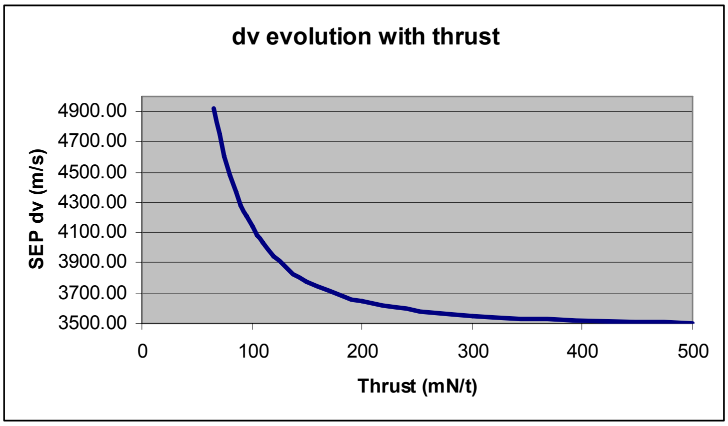
Figure 8 shows the 50mN transfer trajectory.

Figure 8: 2015 SEP trajectory to 1999JU3. 50mN/tonne



The degradation of the solution with respect to the trust level used is much stronger in the other transfer case (2017 launch date for the impulsive transfer). This happens because of both the limited time taken by the transfer and the high impulsive ΔV to be converted into SEP. The effect is a large increase in SEP ΔV (the 65mN solution requires 40% more ΔV than the 500mN case) but, most importantly, a delay in the arrival date at the asteroid: about 3 months if 100mN is considered, 8.5 months with 65mN. Figure 9 shows the exponential increase in ΔV with low thrust-to-mass ratio as of ~ 200 mN/t.

Figure 9: ΔV as a function of thrust for 2016 transfer to 1999JU3



3.2.2 LOW RETURN ΔV CLASS MISSIONS TO NEREUS WITH SEP

Similar analysis is built up for Nereus. These missions exploit the September 2020 return opportunity.

Table 17: Summary of 2015 SEP opportunities to Nereus

thrust/mass (mN/t)	launch dd/mm/yyy	**arrival dd/mm/yyyy**	transfer time days	chem ΔV m/s	SEP ΔV m/s	**SEP ΔV with margin m/s**
500	07/10/2015	**27/04/2020**	1640	700	2089.03	**2172.59**
200	06/10/2015	**03/05/2020**	1647	700	2113.15	**2197.68**
150	05/10/2015	**07/05/2020**	1652	700	2137.28	**2222.77**
100	03/10/2015	**13/05/2020**	1660	700	2213.03	**2301.55**
70	30/09/2015	**28/05/2020**	1678	700	2405.40	**2501.62**
50	26/09/2015	**02/07/2020**	1716	700	2717.80	**2826.52**

The long transfer time and low ΔV of the original chemical transfer make it possible to have a family of SEP transfers where the ΔV is not dramatically increased (50 mN case requires 25% more ΔV than 500mN) and where the nominal arrival date is only delayed by a couple of months for the lowest thrust cases.

3.2.3 MIDDLE RETURN ΔV CLASS MISSIONS TO 1999JU3 WITH SEP

Two interesting roundtrip missions to 1999JU3 have been presented in Table 14: both of them exploit the return trajectory leaving 1999JU3 in July 2023. They both have the same launch date and need the same ΔV. But one has a transfer time longer by 1 year and consequently has a shorter stay time at the asteroid. So these two trajectories would allow a trade off between long transfer-short stay and short transfer-long stay strategies. Table 18 and Table 19 below show the transfer characteristics for the short and long transfer respectively.

Table 18: 2019 SEP short transfer opportunities to 1999JU3

thrust/mass (mN/t)	launch dd/mm/yyy	**arrival dd/mm/yyyy**	transfer time days	chem ΔV m/s	SEP ΔV m/s	**SEP ΔV with margin m/s**
550	15/09/2019	26/01/2022	851	700	1266.28	**1316.94**
325	15/09/2019	26/01/2022	851	700	1276.90	**1327.97**
130	17/09/2019	25/01/2022	848	700	1355.25	**1409.46**
81	20/09/2019	11/01/2022	831	700	1541.56	**1603.22**
62	14/09/2019	12/12/2021	808	700	1806.92	**1879.20**
42	22/08/2019	22/08/2021	720	700	2441.31	**2538.97**

Table 19: 2019 SEP long transfer opportunities to 1999JU3

thrust/mass (mN/t)	launch dd/mm/yyy	**arrival dd/mm/yyyy**	transfer time days	chem ΔV m/s	SEP ΔV m/s	**SEP ΔV with margin m/s**
550	14/09/2019	04/05/2023	1310	700	1269.2399	**1320.01**
325	15/09/2019	04/05/2023	1309	700	1270.5872	**1321.41**
130	16/09/2019	19/04/2023	1293	700	1350.2514	**1404.26**
81	20/09/2019	17/04/2023	1287	700	1537.6897	**1599.20**
62	15/09/2019	02/04/2023	1277	700	1807.2032	**1879.49**
42	02/09/2019	07/11/2022	1145	700	2269.8442	**2360.64**

The interesting result from the first table is that with decrease in thrust the arrival date is actually anticipated. This happens because (as can be seen from very low DSM and rendezvous manoeuvre for this trajectory) the rendezvous with the asteroid occurs in December 2020 (the epoch of the EGA); for the lower thrust levels it turns out to be more convenient to apply the small residual ΔV in a single thrust arc at the time at which the DSM happened in the chemical transfer. The fact that the arrival date is actually anticipated takes away most of the possible benefits of using these transfers, as the waiting time at the asteroid would now be even too long, nearly 2 years. In the second table, it can also be seen that the arrival date is anticipated by several months with the thrust decrease.

3.2.4 SUMMARY OF ROUNDTRIP MISSIONS WITH SEP OUTWARD TRANSFER AND CHEMICAL RETURN

The mission opportunities discussed in the previous chapter are summarised in Table 20. For all transfers a minimum stay time of 3 months has been observed.

Table 20: Roundtrip SEP-CP missions. SEP thrust-to-mass ratio=100mN/tonne

launch	arrival	chem ΔV	**SEP ΔV**	Return	arrival	**ΔV return**	v_entry	**Target**
30/09/2015	01/07/2019	700.00	**1901.91**	11/11/2019	04/12/2020	**7.2**	12001.26	**1999ju3**
03/10/2015	13/05/2020	700.00	**2301.55**	06/09/2020	09/02/2022	**85.2**	12502.21	**Nereus**
11/09/2016	01/12/2019	700.00	**4304.30**	01/02/2020	04/12/2020	**15.9**	12001.26	**1999ju3**
19/09/2019	15/01/2022	700.00	**1489.02**	20/07/2023	04/12/2024	**622.7**	12180.61	**1999ju3**
03/12/2020	04/05/2023	700.00	**1491.52**	20/07/2023	04/12/2024	**622.7**	12180.61	**1999ju3**

3.3 Full SEP roundtrip mission to 1996FG3

All the roundtrip missions presented earlier targeted either 1999JU3 or Nereus due to their better accessibility. Other asteroids constitute very interesting targets from a scientific point of view. Possible roundtrip mission opportunities to 1996FG3 have been looked for, investigating different scenarios regarding propulsion. A return transfer which fulfils the entry velocity requirement is picked up and matched with an outbound transfer to fulfil the stay time requirement.

Table 21: Chemical return from 1996FG3

return dep dd/mm/yyyy	return arrival dd/mm/yyy	dep v_inf (m/s)	ΔV_mcc (m/s)	atm. entry velocity (m/s)	total ΔV m/s	**total ΔV with margin m/s**
17/10/2019	17/10/2021	1265.11	895.00	12500.00	2161.15	**2269.21**

Table 22: Chemical transfer to 1996FG3 matching with return on 17/10/2019

launch (dd/mm/yyyy)	arrival (dd/mm/yyyy)	**transfer time (days)**	dep v_inf (m/s)	dep incl (deg)	ΔV_dep (m/s)	ΔV_mcc (m/s)	arr v_inf (m/s)	ΔV from GTO (m/s)	**total ΔV with margin (m/s)**
21/01/2018	15/04/2019	444	3818.3	6.3	1440.5	0.0	2603.0	4043.5	**4245.66**

The outbound transfer is converted into a SEP according to the same procedure as defined before.

Table 23: 2016 SEP transfers to 1996FG3

thrust/mass (mN/t)	launch dd/mm/yyy	**arrival dd/mm/yyyy**	transfer time days	chem ΔV m/s	SEP ΔV m/s	**SEP ΔV with margin m/s**
550	27/09/2016	**09/05/2019**	942	700	3634.80	**3780.19**
200	04/10/2016	**20/06/2019**	976	700	4035.72	**4197.15**
102	25/10/2016	**02/09/2019**	1027	700	5483.10	**5702.43**
91	02/11/2016	**22/09/2019**	1040	700	6434.57	**6691.95**
87	15/10/2016	**03/10/2019**	1068	700	7439.32	**7736.89**
84	17/10/2016	**06/10/2019**	1069	700	8708.51	**9056.85**
82.5	07/08/2016	**07/10/2019**	1140	700	9442.99	**9820.71**
81	22/05/2016	**11/10/2019**	1219	700	10130.78	**10536.02**

The high ΔV required by the nominal chemical trajectory, combined with the limited transfer time for such a trajectory, translate into a very bad set of SEP transfers to 1996FG3. The SEP ΔVs become exponentially large for the lower thrusts, and most of the resulting trajectory time is spent thrusting. The arrival date at the asteroid is also delayed considerably: only transfers with thrust higher than 130mN/tonne would match (i.e. stay time >3 months) with the nominal departure date (October 2019) for a chemical return leg. SEP return trajectories have also been identified due to the prohibitive chemical ΔVs presented earlier. For each SEP outward transfer in previous table it has been assumed to stay for 3 months at the asteroid and then to come back to Earth with the same thrust (so that only one set of SEP engine is needed for cost-efficiency reasons). All return trajectories enter atmosphere with a velocity of 12.5km/s. Some of the resulting roundtrip transfers are given below.

Table 24: 2016 SEP roundtrip mission opportunities to 1996FG3

T/m (mN/t)	launch dd/mm/yyyy	arrival dd/mm/yyyy	chem ΔV m/s	**outbound SEP dv m/s**	return dep dd/mm/yyyy	return arrival dd/mm/yyyy	**return SEP ΔV m/s**	**total SEP ΔV m/s**
550	27/09/2016	09/05/2019	700	**3780.19**	17/10/2019	17/10/2021	**2247.60**	**6027.79**
130	10/10/2016	27/07/2019	700	**4742.07**	27/10/2019	11/10/2021	**2576.84**	**7318.91**
102	25/10/2016	02/09/2019	700	**5702.43**	03/12/2019	29/09/2021	**3010.04**	**8712.47**
87	15/10/2016	03/10/2019	700	**7736.89**	03/01/2020	02/10/2021	**3708.12**	**11445.01**
81	22/05/2016	11/10/2019	700	**10536.02**	12/01/2020	12/10/2021	**4251.43**	**14787.44**

Table 24 clearly shows again the difficult accessibility of a target as 1996FG3. Total mission duration, however, is not as large as one could expect with a low-thrust system with an average of ~ 5 years. As a reference, using a thrust of 100mN/tonne (at 1AU) would require a total ΔV of 8.7 km/s. Additional heliocentric revolutions could greatly decrease the ΔV required for very low SEP thrust levels because more time would be available to perform the SEP manoeuvres. This implies that the transfer would not be saturated with thrusting arcs and that the thrust would occur at optimal locations (i.e. near perihelion only for aphelion raising manoeuvres). However, the outbound transfer would be extended by at least 1 year.

3.4 Full SEP roundtrip mission to Wilson-Harrington

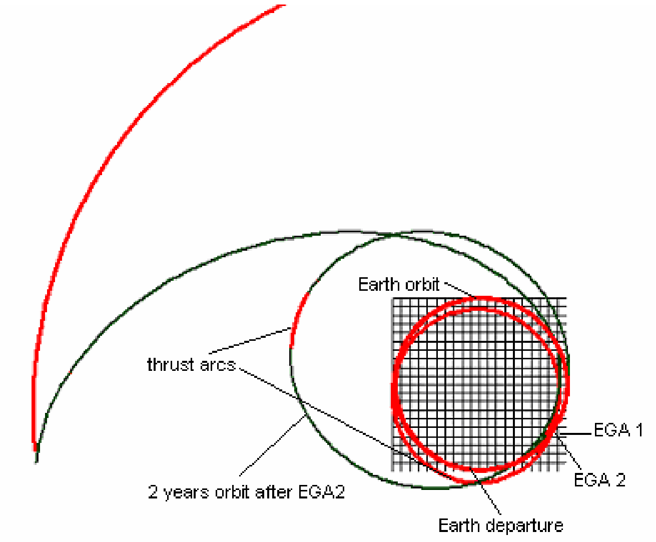
3.4.1 SEP TRANSFERS TO WILSON-HARRINGTON

As a matter of fact, given the high V_{inf_Earth} originally required by the direct chemical transfer when leaving Earth (around 8km/s), a slightly different departure strategy is needed. In this situation, performing two Earth Gravity Assist manoeuvres is the optimal solution. The departure strategy thus becomes:

1. Launch into GTO
2. Raise apogee to lunar crossing orbit by chemical propulsion stage (which requires ~ 700 m/s fromGTO)
3. Perform a Lunar Gravity Assist (typically a V_{inf_Earth} of 1100 m/s is achievable)
4. Leave Earth and thrust for increasing eccentricity of heliocentric orbit and for targeting Earth
5. Come back to Earth after typically 15 months and perform EGA with a V_{inf_Earth} of 5.5km/s
6. Leave Earth on a 2 year period Earth resonant orbit and thrusting at aphelion for increasing eccentricity
7. Come back to Earth 2 years later with the required V_{inf_Earth} (module) and perform a 2nd EGA to achieve correct V_{inf_Earth} (direction)
8. For low thrust systems (<75mN/t) an extra heliocentric revolution has to be added between LGA and first EGA, adding 12 more months to the sequence

The whole sequence lasts typically 39 months for thrust/mass>75mN/t or 51 months for thrust levels between 50mN/tonne and 75mN/tonne. ΔV associated with this strategy are between 2.2 km/s (150 mN/t) and 2.9 km/s (50-75 mN/t). Going below 50mN/t becomes very inefficient, as the transfer tends to be saturated with thrusting arcs and the ΔV losses become quite high. Picture below shows an example of such a strategy for a Jupiter transfer for a thrust/mass of 75mN/tonne.

Figure 10: Example of double EGA departure strategy applied to a Jupiter mission. T/m=75mN/tonne



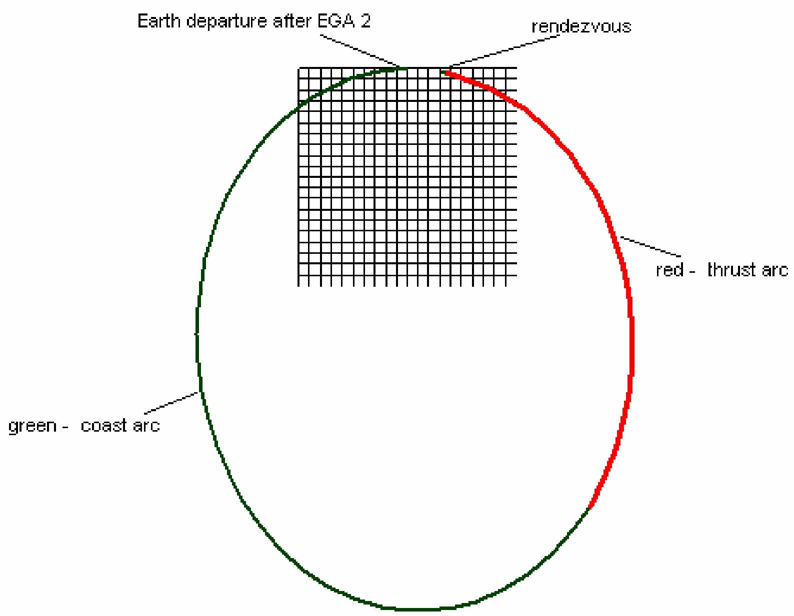
The 60mN/t and 75 mN/t cases have been analysed in detail (Considering a spacecraft mass to be inserted into lunar crossing orbit of 2.4 tonnes):

- 60mN/t translates into a total thrust of 145mN, achievable with a single 150 mN thruster. It requires 51 months for double EGA departure strategy
- 75mN/t translates into a total thrust of 180mN, achievable with a single 200 mN Ion thruster. It requires 39 months for double EGA departure strategy

Table 25: SEP transfers to Wilson-Harrington, arrival in 2022

thrust/mass (mN/t)	launch dd/mm/yyy	**arrival dd/mm/yyyy**	transfer time days	chem ΔV m/s	SEP ΔV m/s	**SEP ΔV with margin m/s**
75	02/07/2015	14/08/2022	2562	700	4124.03	**4288.99**
60	02/07/2014	10/12/2022	3038	700	4347.00	**4520.88**

Figure 11: Final part of the 75mN/tonne transfer to Wilson-Harrington

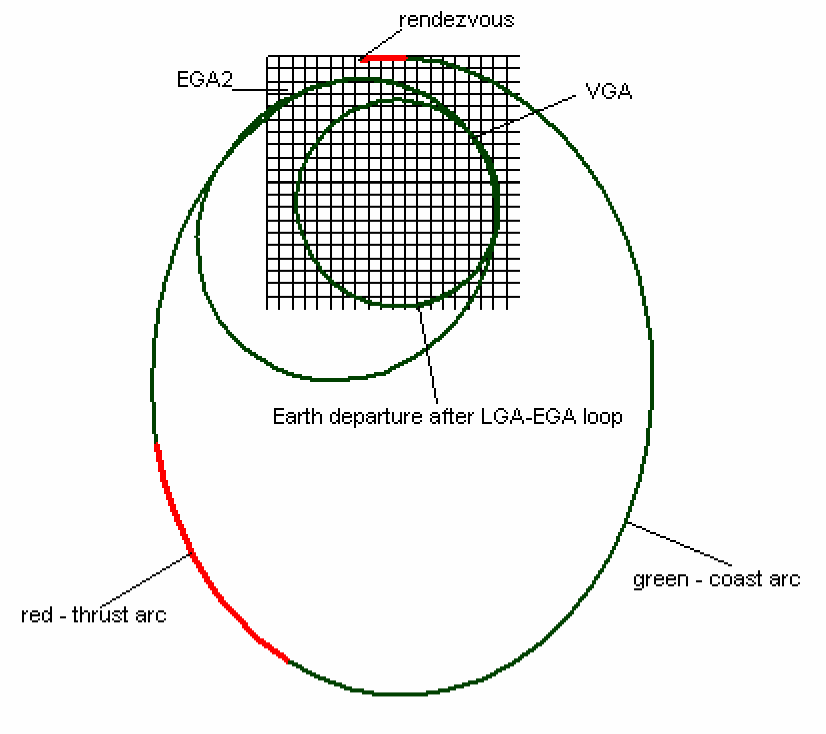


For the very low thrust levels considered up to now (<=75mN/t) the only possibility for a transfer to Wilson-Harrington is to combine the double EGA departure strategy with a direct transfer to the asteroid. Trying to use such a low thrust with VGA-EGA type transfers presented in**Error! Reference source not found.** Table 7 would not be efficient, because in those transfers quite a significant ΔV would have to be applied at 4AU. At this distance from the Sun a SEP system with thrust/mass ratio of 75 mN/t (at 1AU) would only deliver about 6 mN/t. This low thrust level would make it impossible to achieve the required ΔV in an adequate time frame and would not be achievable due to throttling limits on the thrusters. However, with higher thrust levels (T/m~150mN/t or higher) this type of transfers are feasible. The SEP version of transfers in Table 7**Error! Reference source not found.** would use a LGA-EGA to achieve the required escape conditions from Earth. Table below summarises the details of one of these transfers using VGA-EGA in a SEP version and the trajectory after LGA-EGA departure sequence is shown in Figure 12.

Table 26: 150mN/tonne SEP transfer using VGA-EGA to Wilson Harrington

thrust/mass (mN/t)	launch dd/mm/yyy	**arrival dd/mm/yyyy**	transfer time days	chem ΔV m/s	**SEP ΔV with margin m/s**	Path after LGA-EGA
150	07/01/2017	29/10/2024	2812	700	**1714.96**	VE

Figure 12: VGA-EGA SEP transfer trajectory to Wilson-Harrington



3.4.2 SEP RETURNS FROM WILSON-HARRINGTON

As identified in 2.1.4, direct return transfers to Wilson-Harrington have a high arrival $V_{inf-Earth}$ which needs to be reduced to a value of 5.76km/s to allow atmospheric entry velocity within 12.5km/s. The optimized way to deal with this problem is to:

- Apply an initial burn to leave the asteroid and target Earth,
- Reach Earth with a $V_{inf-Earth}$ of typically 8km/s
- Perform an EGA to lower aphelion and reach 2 year period orbit
- Thrust in order to increase eccentricity, providing a ΔV of typically 500m/s
- Rendezvous with Earth 2 years after EGA with a $V_{inf-Earth}$ <5.76km/s

This strategy is basically the reverse of the 2nd EGA in the double EGA departure loop.

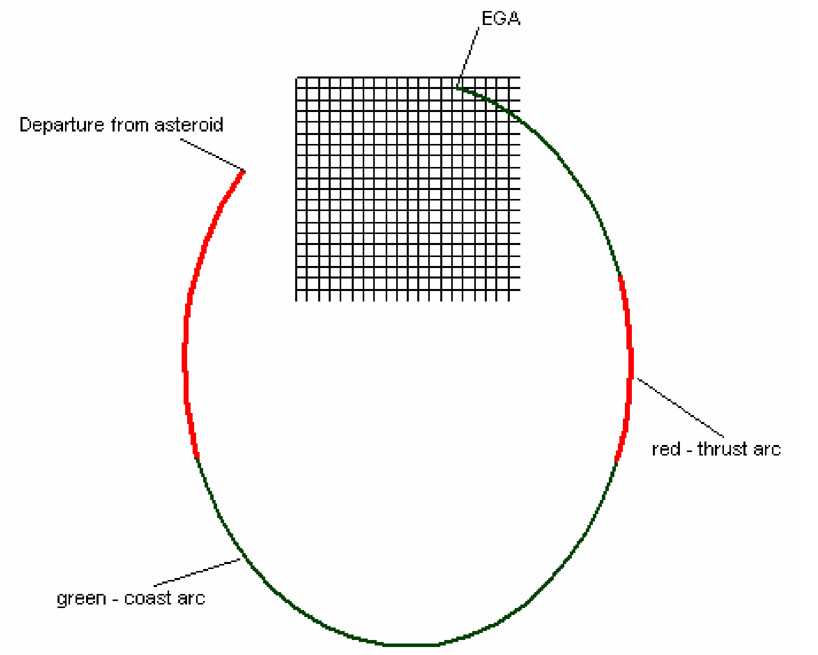
3.4.3 ROUNDTRIP MISSIONS TO WILSON-HARRINGTON

Table below provides a summary of two roundtrip missions to Wilson-Harrington for the scenarios using double EGA at departure and direct transfer from second EGA to the asteroid. It has to be noticed that if one assumes the same SEP installation for both legs of the mission, then the T/m ratio for the return leg would be considerably higher, as the s/c mass for the return mission is lower than for the outbound part of the transfer, due to fuel consumption and staging. So the thrust/mass ratio (75 mN/t and 60 mN/t) assumed in the table below refers to the outbound part of the mission.

Table 27: Roundtrip SEP opportunities to Wilson-Harrington

launch dd/mm/yyyy	arrival dd/mm/yyyy	chem Δv m/s	outbound SEP Δv m/s	departure dd/mm/yyyy	Earth arrival dd/mm/yyyy	return SEP Δv m/s	**total SEP Δv m/s**	**Mission duration (years)**
02/07/2015	14/08/2022	700	4330.23	08/01/2023	28/08/2028	1584.31	**5914.53**	**12.97**
02/07/2014	10/12/2022	700	4564.35	30/12/2022	28/08/2028	1579.46	**6143.81**	**13.95**

Figure 13: First part of 2023 return trajectory from Wilson-Harrington. T/m=75mN/tonne

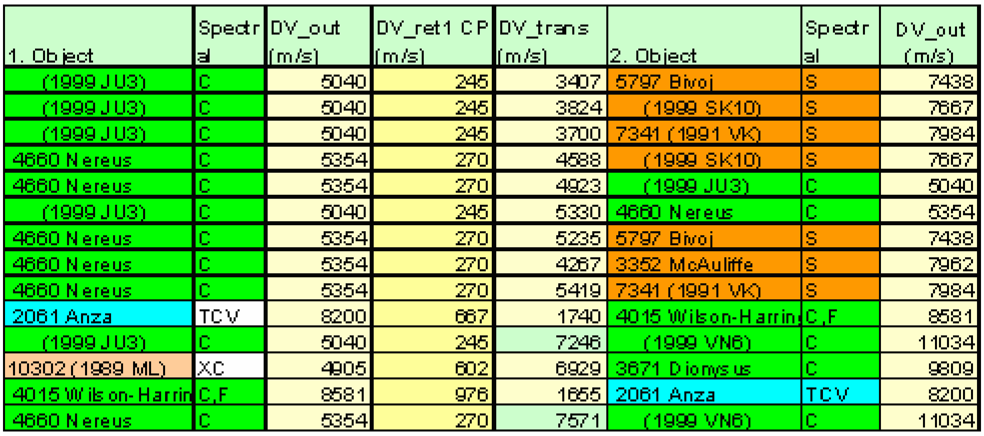


As can be seen from Table 27, SEP return missions to such a target are very long, about 13 years. A higher thrust installation (as for example 150mN/t) would reduce the mission time. No such solution has been provided, because for the specific outbound transfer presented in Table 26 there is no return opportunity with a stay time less than 3 years. With further investigation it is certainly possible to find such a solution, for example by looking at other VGA-EGA type transfers or by placing constraints to the arrival time at the asteroid (or departure epoch from the asteroid) for the presented mission. However, total mission duration would hardly be less than 11years in any case.

4 DOUBLE TARGETS

The analytical model has been initially used to evaluate the feasibility of a 2 asteroid mission which does not take into account phasing and transfer optimisation. The following pairs have been identified ranked along the required ΔV. The other constraint is that the first visited target shall be a C-type asteroid so that the risk associated with a double asteroid mission is minimized in the sense that the target of primary scientific interest is visited first.

Table 28: Double asteroid mission opportunities. Analytical analysis



1. Object	Spectral	DV_out (m/s)	DV_ret1 CP (m/s)	DV_trans (m/s)	2. Object	Spectral	DV_out (m/s)
(1999 JU3)	C	5040	245	3407	5797 Bivoj	S	7438
(1999 JU3)	C	5040	245	3824	(1999 SK10)	S	7667
(1999 JU3)	C	5040	245	3700	7341 (1991 VK)	S	7984
4660 Nereus	C	5354	270	4588	(1999 SK10)	S	7667
4660 Nereus	C	5354	270	4923	(1999 JU3)	C	5040
(1999 JU3)	C	5040	245	5330	4660 Nereus	C	5354
4660 Nereus	C	5354	270	5235	5797 Bivoj	S	7438
4660 Nereus	C	5354	270	4267	3352 McAuliffe	S	7962
4660 Nereus	C	5354	270	5419	7341 (1991 VK)	S	7984
2061 Anza	TCV	8200	667	1740	4015 Wilson-Harrin	C,F	8581
(1999 JU3)	C	5040	245	7246	(1999 VN6)	C	11034
10302 (1989 ML)	XC	4905	602	6929	3671 Dionysus	C	9809
4015 Wilson-Harrin	C,F	8581	976	1655	2061 Anza	TCV	8200
4660 Nereus	C	5354	270	7571	(1999 VN6)	C	11034

Since transfers between Earth and these asteroid have already been identified and the transfer between them seems to be one of the most interesting for double pairs, some analysis has been performed on the Nereus-1999JU3 pair. The Wilson-Harrington-Anza pair has also been investigated. Only chemical transfers have been considered, as the goal of this analysis is to assess the feasibility of such type of mission. Chemical transfer ΔVs are good indicators of accessibility of the asteroid pairs, and can help estimating the ΔV for an analogous SEP mission. The double target scenario was assumed to be Earth-Target1-Target2-Earth. Results are indicated in Table 29 and Table 30. But other scenarios exist (e.g. Earth-target1-Earth return of 1st ERV + parallel transfer to target2 of 2nd ERV-Earth return of 2nd ERV). In particular, the alternative scenario depicted in Figure 14 is interesting and could save a substantial amount of propellant due to the EGA. However, the need to comply with the V_{atm} and the requirements on the EGA might be an issue. This was not studied further in this context due to the very long duration (and therefore high operational cost) of such a mission design.

Figure 14: Alternative transfer strategy for a double asteroid mission

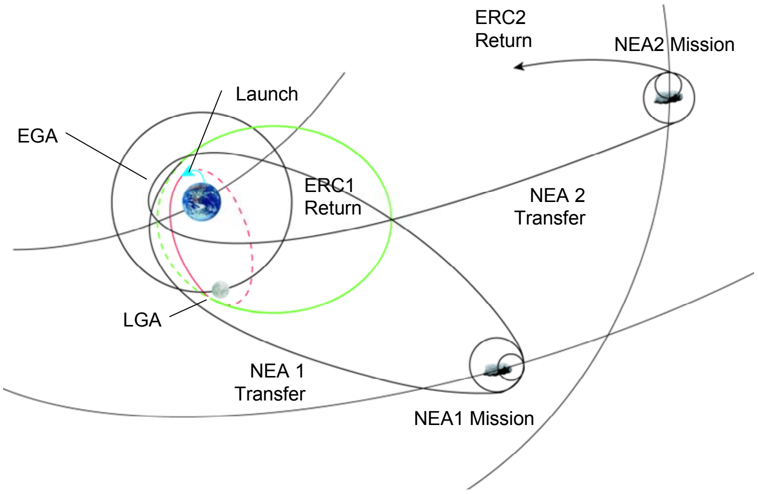


Table 29: Double asteroid mission transfers to Nereus and 1999JU3

targets	**launch**	RV1	ΔV1	dep1	RV2	ΔV2	dep2	**arrival**	ΔV3	**total ΔV**
Nereus - 1999JU3	**26/1/15**	7/5/18	2454	25/5/18	5/2/20	4595	5/5/20	**5/12/20**	42	**7091**
1999JU3 - Nereus	**6/12/16**	31/3/18	2502	14/6/18	20/8/20	4320	6/9/20	**9/2/22**	85	**6907**
1999JU3 - Nereus	**4/12/15**	30/4/18	2275	14/6/18	20/8/20	4320	6/9/20	**9/2/22**	85	**6681**
Nereus - 1999JU3	**26/1/17**	10/3/20	2675	21/8/20	19/7/22	5754	20/7/23	**4/12/24**	623	**9052**
Nereus - 1999JU3	**26/1/17**	10/3/20	2675	17/8/20	20/8/23	4311	20/7/23	**4/12/24**	623	**7609**
1999JU3 - Nereus	**4/12/15**	30/4/18	2275	14/6/18	20/8/20	4320	8/3/22	**10/2/24**	651	**7246**
1999JU3 - Nereus	**6/12/16**	31/3/18	2502	14/6/18	20/8/20	4320	8/3/22	**10/2/24**	651	**7473**
1999JU3 - Nereus	**5/12/16**	11/7/19	2158	2/9/19	4/11/21	6173	8/3/22	**10/2/24**	651	**8982**

Mission opportunities require no less than 6.7 km/s. Total mission time varies but never takes less than 5.2 years (opportunity No2). Even then the stay time at the 2nd target is 2 weeks only and not compliant with the requirement of 3 months. If one wants to be compliant with 3 months, opportunity No7 has to be picked up and leads to a mission duration of ~ 7.2 years.

Table 30: Transfer between Wilson-Harrington and Anza

Wilson	Anza	transfer time	dep v_inf	ΔV_mcc	arr v_inf	**ΔV**
05/05/2018	13/01/2022	1328	510.9	645.1	339.6	**1570.4**
17/08/2022	19/06/2025	1022	1565.8	652.0	721.8	**3086.6**
25/08/2022	16/11/2028	2241	929.3	448.5	1791.9	**3328.2**
07/12/2026	13/04/2032	1926	559.4	502.6	1422.4	**2608.6**

Transfer ΔV is much lower than in the Nereus-1999JU3 case. The drawback of this pair lies in the transfer times to asteroids and from asteroid to asteroid. Assuming that a chemical mission would be possible (unrealistic), Table 6 showed that it takes typically 3 years to go to Wilson-Harrington. To this we have to add typically 3 more years for the inter-asteroid transfer and a similar amount of time for the transfer from Anza to Earth. So, provided the phasing between all the legs of the transfer is perfect, the total mission duration would be at least 10 years, which is prohibitively long. The situation is yet much worse for a SEP case.

The conclusion which can be drawn from the previous considerations is that a 2 asteroid mission (whether ASR or AIS) would require the use of SEP. In addition, the mission duration always is higher than 6/7 years in an unrealistic chemical case which implies an even longer mission duration when SEP is used. Combining these two facts indicate that the cost of such a mission scenario does not comply with the cost-efficiency approach of the desired mission design. The transfer to two asteroids has therefore been discarded.

5 BACK-UP TARGETS

Analytically, 10 targets seem to be better accessible than 1999JU3.

Table 31: Targets (unknown or S-type) easier to access than 1999JU3 (analytically)

Object	a (AU)	e	i (deg)	w (deg)	Node (deg)	M (deg)	q (AU)	Q (AU)	P (yr)
1996XB27	1.18888	0.057901	2.465125	57.61919	179.581922	186.7575	1.12	1.26	1.30
89136 (2001 US16)	1.355646	0.252713	1.904091	66.97992	176.035504	297.3445	1.0131	1.7	1.58
2002 NV16	1.237608	0.220024	3.507347	179.3967	183.589047	109.4368	0.9653	1.51	1.38
1998 HG49	1.200845	0.112671	4.196075	324.031	44.9658721	134.5045	1.0655	1.34	1.32
25143 Itokawa	1.32023	0.28034	1.62341	162.7987	69.10243	322.708	0.953	1.69	1.52
2003 GA	1.281591	0.191283	3.841425	66.69967	192.981621	232.6336	1.0364	1.53	1.45
2004 KE1	1.299591	0.181204	2.881485	282.8901	43.260139	272.9305	1.0641	1.54	1.48
65717 (1993BX3)	1.394697	0.280599	2.789049	289.8567	175.627527	235.6838	1.0033	1.79	1.65
2000EA14	1.116798	0.202524	3.554633	206.0371	203.994862	95.6524	0.8906	1.34	1.18
1994CJ1	1.489131	0.324899	2.304729	64.95869	172.273544	27.61298	1.0053	1.97	1.82
1999JU3	1.189118	0.190028	5.88489	211.3165	251.695884	147.267	0.963	1.41	1.30

Mission analyses show the best actual transfer opportunities to these targets.

Table 32: Roundtrip transfer opportunities from more accessible targets (unknown or S-type)

target	launch	launch decl (deg)	total dv out (m/s)	Earth arrival	dv return (m/s)	stay time (days)	**total mission (yr)**	**total dv (m/s)**
1996XB27	27/03/2018	13.21	2107.26	25/03/2023	1054.15	369	**4.99**	**3161.41**
1996XB27	28/03/2019	2.18	2834.64	24/03/2023	1054.66	265	**3.99**	**3889.29**
2001US16	21/05/2023	1.09	2416.20	10/04/2026	805.07	123	**2.89**	**3221.27**
2001US16	21/05/2023	1.09	2416.20	17/04/2026	787.31	173	**2.91**	**3203.51**
2001US16	18/05/2015	-4.89	2408.95	10/04/2018	1205.47	157	**2.89**	**3614.42**
2002NV16	26/09/2020	-13.09	1935.10	27/09/2024	403.15	7	**4.00**	**2338.25**
2002NV16	27/09/2020	-16.50	2241.53	27/09/2024	403.15	504	**4.00**	**2644.67**
2002NV16	26/09/2016	-16.63	2254.14	25/09/2020	697.69	88	**4.00**	**2951.83**
2002NV16	20/09/2017	-8.26	2440.08	25/09/2020	697.69	172	**3.01**	**3137.77**
1998HG49	02/11/2018	66.57	2006.42	07/11/2023	704.39	368	**5.01**	**2710.81**
1998HG49	02/11/2022	69.39	2020.61	08/11/2027	659.31	403	**5.02**	**2679.93**
Itokawa	12/05/2016	-26.04	2153.96	05/05/2021	1305.15	221	**4.98**	**3459.11**
Itokawa	11/05/2019	-26.76	2243.31	02/05/2024	1191.94	204	**4.98**	**3435.26**

6 REFERENCES

[Agnolon07] Agnolon D. & Al., “Study overview of the Near Earth Asteroid sample return”, ESA public document, May 2007

[Atzei07] Atzei. A., “Margin philosophy for assessment studies”, SCI-A/2003/302/AA, issue 3.2, 11 December 2006

7 ACRONYMS

AIS	Asteroid In-Situ (mission)
ASR	Asteroid Sample Return (mission)
AU	Astronomical Unit
DSM	Deep Space Manoeuvre
EGA	Earth Gravity Assist
GTO	Geostationary Transfer Orbit
LGA	Lunar Gravity Assist
RV	Rendez-Vous
VE	Venus-Earth
VEE	Venus-Earth-Earth
VGA	Venus Gravity Assist
ΔV	Delta-V