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1st ACT Global Trajectory Optimisation Competition: Results found at DEIMOS Space

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Abstract

This paper presents the analyses performed by DEIMOS Space S.L. in response to the 1st ACT Competition on Global Trajectory Optimisation issued by the Advanced Concepts Team at ESA. Being the subject of the Contest within one of the main activities performed at the Mission Analysis Section at DEIMOS, it was decided that participating to the Contest on the basis of our expertise and by making use of our tools would be a challenging and motivating test. DEIMOS Space hereby presents a summary of the assessment on the proposed problem based on a synergic approach to Global Optimisation which has rendered a large number of possibilities to hit the asteroid in the conditions proposed in the statement of the problem. Only a small number of them were finally refined until complete convergence. The best solution is based on an arriving retrograde trajectory towards the target asteroid, reached after successfully finding a Jupiter–Saturn–Jupiter final sequence of swingbys.

1. Introduction

The evaluation of the threat posed on the Earth by the potentially hazardous asteroids (PHA) is currently a hot topic in Astronautics and Global Security. Humankind has to demonstrate in the years to come the capability to lower the threat that some of those NEA could pose on the Earth in the short and medium term and the mitigation measures that could be taken, among which a considered option is deflecting the asteroid by a direct impact.

The optimisation problem given in the 1st ACT Global Trajectory Optimisation Competition [1] allows characterising the current capabilities of the Aerospace community in designing an optimal trajectory to hit an asteroid to deflect it. The test case is asteroid 2001-TW229.

The statement of the given problem suggests, right from the beginning, the path to follow in order to find suitable solutions… i.e. make a proportioned use of both planetary swingbys and low-thrust to achieve the best possible impact conditions at the asteroid.

The proposed cost function in [1] evaluates the amount of energy that can be transferred to the asteroid assuming a perfectly inelastic collision. This is in fact a preliminary approach to the actual impact performances that could be finally achieved, where neither ejecta effects nor other impact effects are included.

The proposed thrust modulus for the assessment is quite low, broadening and flattening the solution space. The thrust level only allows to faintly interacting on the trajectory definition, thus having to largely rely on the use of massive bodies to achieve large changes in velocity and thus achieve the mission goal.

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The proposed cost function implied that the best options would be those that allowed encountering the asteroid in opposed orbit to the S/C, i.e. the S/C having a retrograde orbit at impact. For the spacecraft to reach a retrograde orbit, swingbys in the Giant planets are required, due to the strong effect they can influence on the spacecraft. Thus, options for swingby at Jupiter and Saturn to finally target to the asteroid were searched for from the beginning.

The proposed departure delta-V in [1] is slightly less than the required escape velocity to reach Venus, thus a thrust arc, or even a supporting Earth swingby is generally required to reach another body than Earth after launch. Reaching Venus, already allows multiplying the number of solutions, which again broadens when other bodies are sequentially encountered.

Making a swingby at Jupiter prior to reaching 2001-TW229 was demonstrated as insufficient at a given point in the analysis. Therefore, it was decided to also involve Saturn, which in fact resulted of very much help in providing useful and optimal missions.

Our method made use of such considerations and a hybrid optimisation process in order to reach optimal solutions. The process first allowed performing a systematic scan of the global solution space, followed by a manual selection of the best-suited options which were finally optimised by means of a local low-thrust optimiser.

This paper first presents a description of the utilised method, followed by the application to the proposed problem in [1] and the results obtained at the Competition which left DEIMOS solution as the second in the contest. Finally the conclusions are provided.

2. Description of the method

The methodology employed to reach the solution of the problem has been based on a three-step strategy:

1. Systematic search of ballistic options with powered swingbys complying with the problem constrains. The powered swingbys are so in the sense that manoeuvres at the infinite of the arrival hyperbola branch or the departure hyperbola branch are allowed.
2. Selection of best-suited solutions under a number of criteria.
3. Refinement of the best solutions by means of a low-thrust local parameter optimiser where the ballistic manoeuvres are substituted by low-thrust arcs.

2.1. Systematic Ballistic Search

This process was based on the following subprocesses: manual selection of the sequence of massive bodies to visit by testing and rejection, full scanning of ballistic solutions by means of a Lambert Solver, non-linear programming optimisation of the best ballistic cases complying with the problem constraints.

In the mentioned processes the main assumptions made are: use of multiple planetary swingbys, inclusion of regular and singular (180° and 360° transfers at the same body) swingbys and discrete manoeuvres at the arrival branch or at the departure branch of the swingby hyperbolas. A summary of the process and assumptions can be found in [2].

The intense and complete scanning of solutions ensures that the best optimal cases are not missed in the process, which solutions are improved by means of a local non-linear programming optimiser.

2.2. Best cases selection

Among all the obtained solutions in the previous process complying with the trajectory constraints, the best solutions were selected for a last refined optimisation. The main criteria considered for this selection was, in order of importance:

- best cost function values;
- low total required delta-V; and
- low mission duration.

Under such constraints, only a few number of solutions are left for the final step.

2.3. Solution refinement

The refinement of the proposed solutions was executed by making use of a local constraint optimiser [3]. The tool performs the optimisation of the selected cost function by means of a direct method and a parameter optimisation of the whole proposed trajectory, playing with the following variables: event times (departure, arrival, swingbys, thrust switches, etc.), departure velocity vector, arrival velocity vectors to all the swingby bodies and to the target body, B-plane impact vectors for all the swingby bodies and the parameters defining a given law on the two thrust angles for each thrust arc.

To the posed optimisation problem, the following constraints were applied: maximum allowed changes in the event times, minimum/maximum/exact durations of any of the thrust/coast arcs, given departure excess velocity modulus (as it is the case for the proposed problem at 2.5 km/s), and minimum swingby heights at each massive body.

The problem is ensured to end up finding with such final process the searched for solution complying with all the imposed constraints and making use of the provided dynamic conditions and the initial ballistic solution.

3. Application of the method to the problem

3.1. Systematic Ballistic Search

Within this process the following types of trajectories were manually tested and seen to provide with feasible transfers with high cost function: EVEMEJSA, EVEVEVEJSA, EVVEEVVEVEJSA (V stands for Venus, E for Earth, M for Mars, J for Jupiter, S for Saturn and A for the asteroid). Other profiles were also constructed but were disregarded for not providing the high cost function values achieved by the above options.

3.2. Best cases selection

Among the obtained solutions, the best case in each combination of swingbys under the criteria mentioned in Section 2.2 was selected for ulterior convergence with the local optimiser.

3.3. Solution refinement

Each of the selected solutions for in any of the combination of swingbys was let converge assuming that the discrete manoeuvres in the ballistic paths were substituted by low-thrust arcs. The optimiser played with the thrust times, swingby times, swingby conditions and thrust direction laws in order to find the optimal solution under the imposed constraints.

4. Competition results

4.1. Systematic Ballistic Search

The proposed strategy for this first step allowed obtaining myriads of solutions within the proposed conditions, which at the same time formed families of solutions with similar performances.

In summary, almost 47,000 solutions with a cost function above $1.6 \times 10^6\ \mathrm{kg\,km^2/s^2}$ were found by means of this scanning procedure. All the obtained missions were graphically represented together in a number of plots to obtain a clear understanding of the best feasible missions that comply with the expected profile and constraints.

Fig. 1 provides the arrival relative velocity at 2001-TW229 as function of the launch date. Mission opportunities roughly every 300 days are possible. Fig. 2 provides the arrival date to the asteroid as function

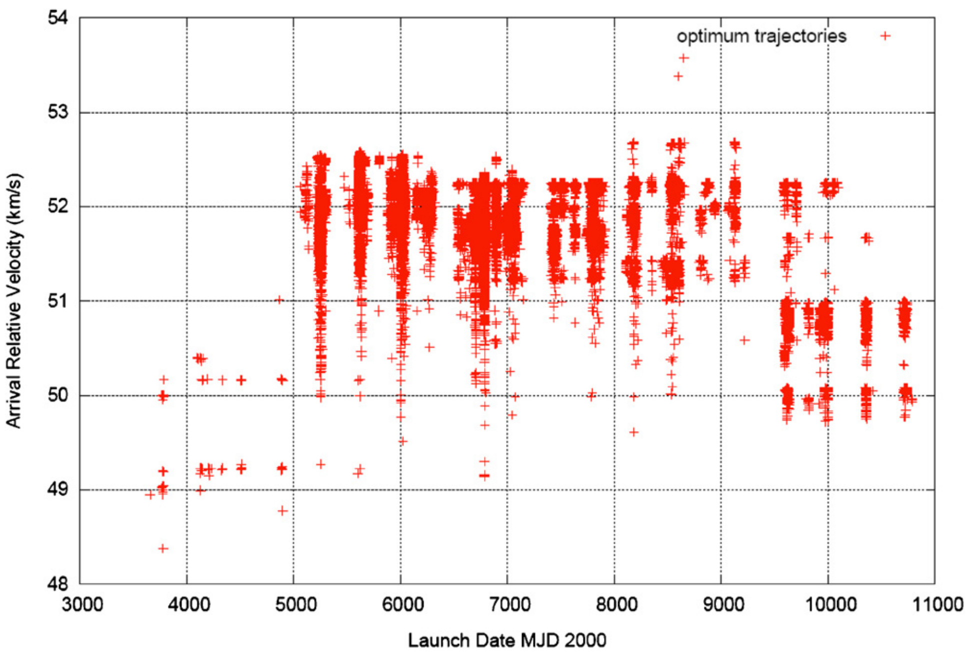

Fig. 1. Arrival relative velocity vs. launch date for all the cases.

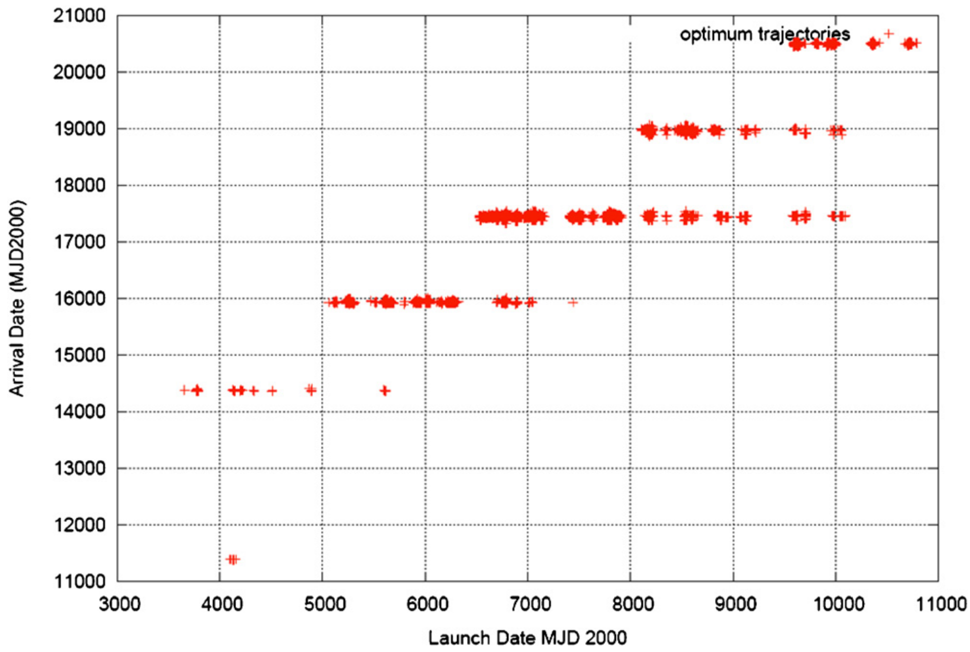

Fig. 2. Arrival date vs. launch date for all the cases.

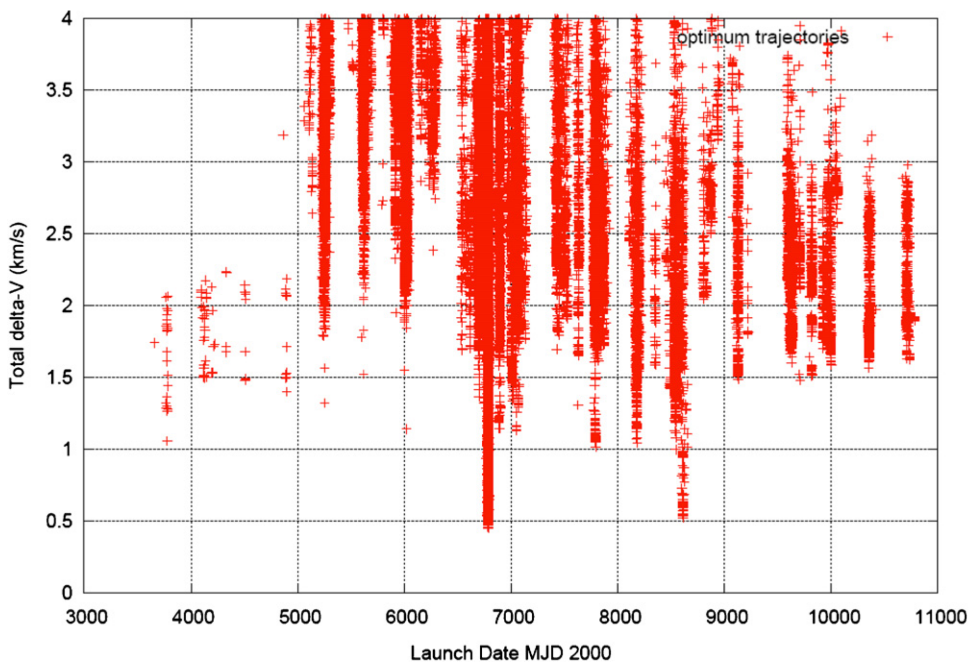

Fig. 3. Total discrete delta-V vs. launch date for all the cases.

of the departure date, where it can be clearly seen the opportunities to hit the minor body occur roughly every 1520 days, which is the period of the asteroid. In fact, the missions are always obtained such that the impact occurs close to the perihelion of 2001-TW229.

Fig. 3 provides the total required discrete delta-V for the found missions, where it can be seen that the opportunities requiring the least propellant are the ones departing in 2018 and 2023, probably due to a more favourable alignment of all the visited planets.

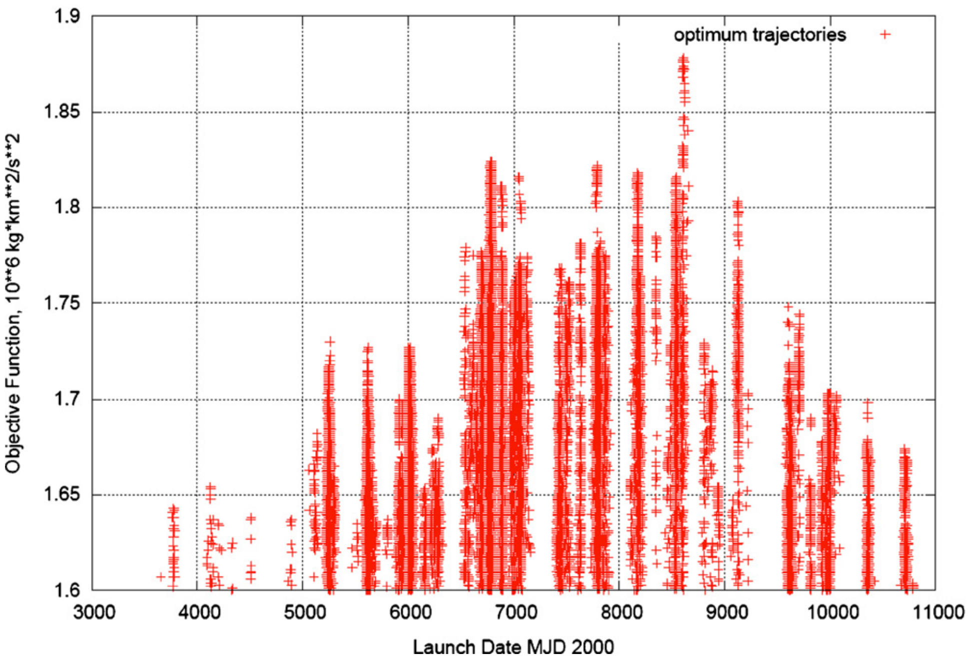

Fig. 4. Cost function vs. launch date for all the cases.

Table 1
Some of the best solutions obtained in the Systematic Ballistic Search

Mission	Profile	Departure date (MJD2000)	Arrival date (MJD2000)	Ballistic cost function ($10^6\,\mathrm{kg\,km^2/s^2}$)	Chemical delta-V (km/s)
A (Case 3772)	EVEVEJSA	6748.5	17423.0	1.753	1.414
B (Case 4698)	EVEVEJSA	6786.9	17466.5	1.739	2.227
C (Case 12822)	EVEVEJSA	7786.2	17441.0	1.729	1.870
D (Case 50B)	EVEMEJSA	9616.1	17461.3	1.739	2.252
E (Case 4662C)	EVEVEVEJSA	6786.1	17421.2	1.822	0.482
F (Case 43229D)	EVVEEVVEVEJSJA	8608.6	18956.1	1.878	0.613

Fig. 4 provides the obtained cost function as function of the launch date, which also presents the best values for launches in 2018 and 2013, as presumably from the previous plot. A maximum over $1.88 \times 10^6\,\mathrm{kg\,km^2/s^2}$ appears for launches in 2023. It could be also seen that in general, the more the time allowed for the mission, the higher the cost function. The maximum of the cost function can be reached in missions of 28.3 years, all within the allowed limit of 30 years. It is also remarkable that very good values of the cost function can be obtained for missions of roughly 20 years.

4.2. Best cases selection

Under the proposed criteria in Section 3.2, the missions presented in Table 1 were selected for refinement. However, only cases E and F were finally refined, extracted from the best performing families.

A solution with an even better cost function of $1.875 \times 10^6\,\mathrm{kg\,km^2/s^2}$ and mission duration of 28 years could not be put to convergence due to lack of time before contest deadline.

4.3. Solution refinement

4.3.1. Case E

Present case had the following manoeuvres obtained in the Systematic Ballistic Search: 215 m/s at Earth departure and 267 m/s prior to arriving to Jupiter. The first delta-V is too high to be implemented by the low-thrust system in the short arc between Earth and Venus,

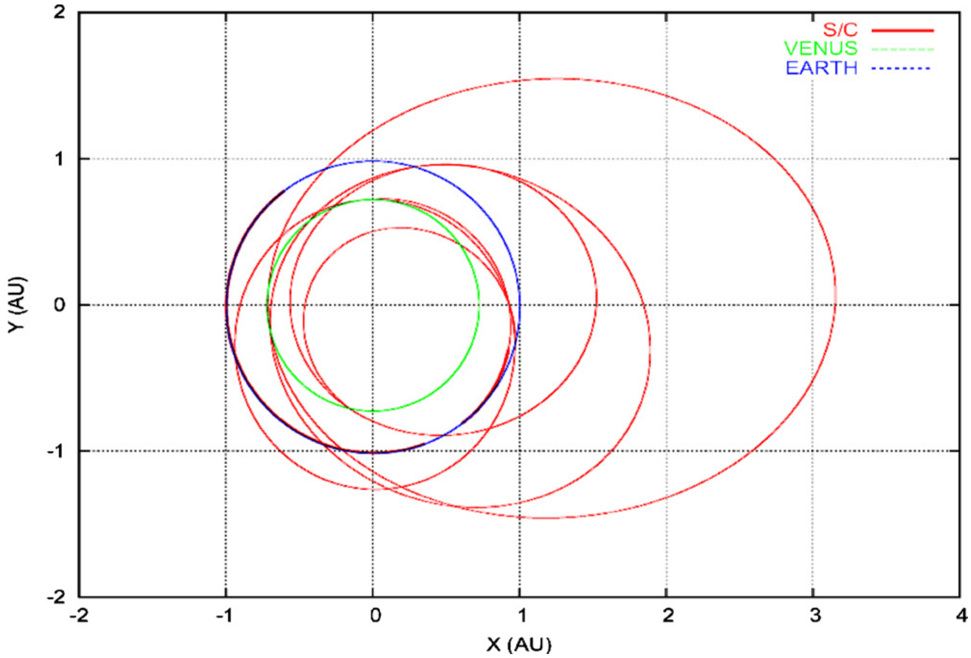

Fig. 5. Projection of the inner tour with swingbys at Earth and Venus (solution E).

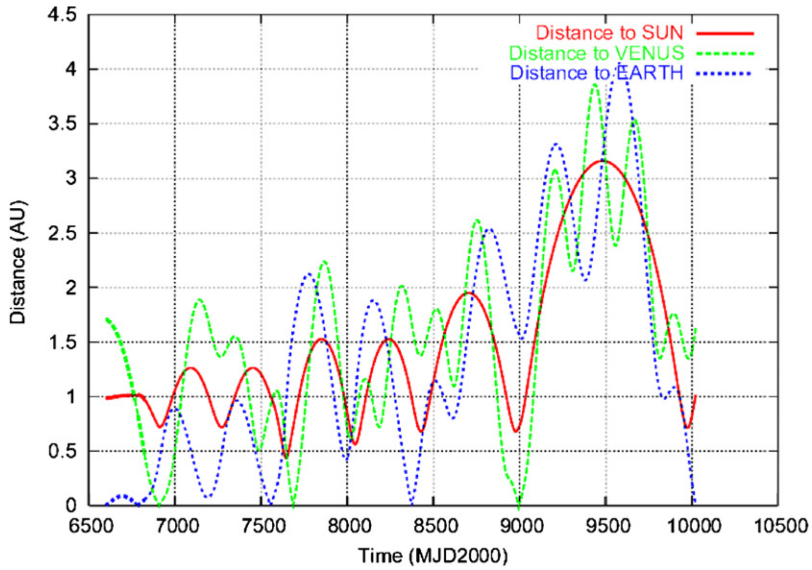

Fig. 6. Distance to the main bodies in the inner tour (solution E).

thus it was decided to launch six months before and perform an extra Earth swingby. Such strategy allowed obtaining convergence in the proposed area with the low-thrust manoeuvre split just after launch and after the Earth swingby.

With the mentioned addition, the solution structure is finally (symbols as before, plus T standing for a thrust arc and C for coast arc):

E_0-T-C-E_1-T-C-V_1-C-E_2-C-V_2-C-E_3-C-V_3-C-E_4-C-T-J-C-S-C-A.

The final obtained cost function for this case is $1.789510 \times 10^6\,\mathrm{kg\,km^2/s^2}$. It differs from the ballistic value of $1.822 \times 10^6\,\mathrm{kg\,km^2/s^2}$ presented in Table 1

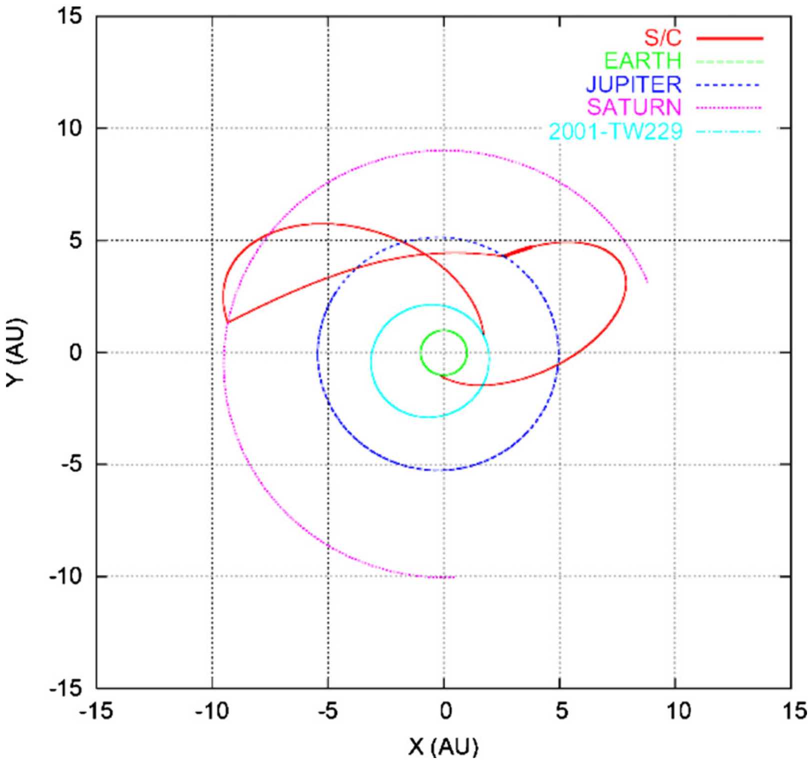

Fig. 7. Projection of the outer tour with swingbys at Earth, Jupiter and Saturn (solution E). *Note*: Do observe the final retrograde motion of the S/C after the swingby at Saturn. Thrust arcs are represented in thicker lines.

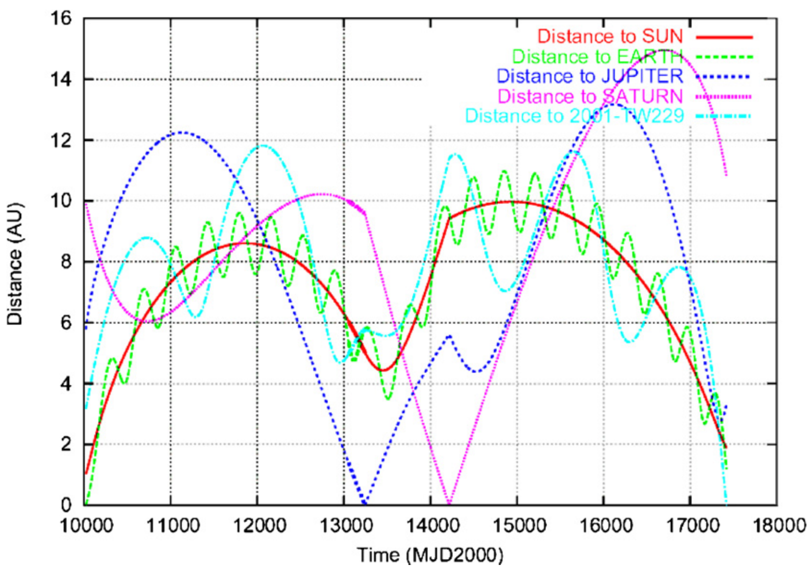

Fig. 8. Distance to the main bodies in the outer tour (solution E).

mainly due to the increased mass consumption required by the low-thrust performance. The duration of the whole mission is 29.627 years, slightly lower than the imposed limit.

Figs. 5 and 6 present a number of plots in the so-called inner tour that expands from departure to the last Earth swingby. The first figure presents the projection of the trajectory in the ecliptic together with the orbits of Earth

Table 2
Reference values at the main trajectory events (solution E)

Main event	Event date	Thrust switch	Arcs	Duration (days)
Departure	26/01/2018 14:38:13	On	Thrust	167.4784
Thrust switch	13/07/2018 02:07:03	Off	Coast	17.3794
Earth swingby	30/07/2018 11:13:21	On	Thrust	38.576
Thrust switch	07/09/2018 01:02:43	Off	Coast	85.506
Venus swingby	01/12/2018 13:11:21	–	Coast	645.0139
Earth swingby	06/09/2020 13:31:25	–	Coast	132.4091
Venus swingby	16/01/2021 23:20:30	–	Coast	687.5617
Earth swingby	05/12/2022 12:49:20	–	Coast	621.4137
Venus swingby	17/08/2024 22:45:02	–	Coast	1025.9896
Earth swingby	09/06/2027 22:30:03	–	Coast	3034.6637
Thrust switch	30/09/2035 14:25:44	On	Thrust	189.4053
Jupiter swingby	07/04/2036 00:09:24	Off	Coast	972.631
Saturn swingby	05/12/2038 15:18:07	–	Coast	3202.5692
Arrival to asteroid	12/09/2047 04:57:47	–	End	

Table 3
Reference values at the planetary swingbys (solution E)

	Epoch (MJD2000)	S/C Mass (Kg)	Arrival velocity in J2000.0				Flyby radius (km)
			X-component (km/s)	Y-component (km/s)	Z-component (km/s)	Modulus (km/s)	
Earth departure	6600.610	1500.00	0.03964	1.20307	−2.19113	2.50000	
Earth swingby 1	6785.468	1476.40	0.06995	−1.16643	2.35545	2.62937	36201.4
Venus swingby 1	6909.550	1470.96	−2.47155	−1.94990	−3.88806	5.00277	21889.6
Earth swingby 2	7554.564	1470.96	−7.68564	0.64809	0.74554	7.74887	10488.7
Venus swingby 2	7686.973	1470.96	−5.66290	−13.02923	−3.40751	14.60960	7371.6
Earth swingby 3	8374.534	1470.96	−1.37294	−13.05499	−5.33917	14.17125	15102.9
Venus swingby 3	8995.948	1470.96	−6.01486	−7.47798	−3.17862	10.10952	8920.3
Earth swingby 4	10021.938	1470.96	−1.10603	−14.72756	−8.39462	16.98805	8102.9
Jupiter swingby 1	13246.007	1444.27	−0.42394	−11.43879	−4.69741	12.37300	634039.3
Saturn swingby 1	14218.638	1444.27	−15.23663	0.32662	0.51792	15.24892	71840.0
2001-TW229 arrival	17421.207	1444.27	12.95700	−47.45967	−15.74819	51.65568	

and Venus. The thrust arcs are represented with a thicker line. The next figure presents the relative distances to the two planets and the Sun (the swingbys can be observed crossing the abscissa axis).

Figs. 7 and 8 present the same plots for the outer tour from the last Earth swingby to the impact on 2001 TW229.The swingbys at Jupiter and Saturn can be clearly observed.

Table 2 provides the mission timeline and the main events occurring along the mission in the proposed profile. Table 3 presents the main values of interest in the swingbys for the whole trajectory profile (in the first line the "arrival velocity" concept refers in fact to the Earth escape velocity).

4.3.2. *Case F*

The proposed solution for this trajectory is the following based on the EVVEEVVEVEJSJA ballistic profile:

$$\mathbf{E_0\text{-}T\text{-}C\text{-}T\text{-}C\text{-}V_1\text{-}C\text{-}V_2\text{-}C\text{-}E_1\text{-}C\text{-}E_2\text{-}C\text{-}V_3\text{-}C\text{-}V_4\text{-}T\text{-}C\text{-}E_3\text{-}T\text{-}C\text{-}V_5\text{-}C\text{-}E_4\text{-}T\text{-}J_1\text{-}C\text{-}S\text{-}C\text{-}J_2\text{-}C\text{-}A}.$$

As it can be observed it is a quite complex trajectory profile with: four Earth swingbys, five Venus swingbys, two Jupiter swingbys and one Saturn swingby.

Present case had the following manoeuvres obtained in the Systematic Ballistic Search: 181 m/s at Earth departure, 104 m/s after V_4, 40 m/s after E_3 and 287 m/s

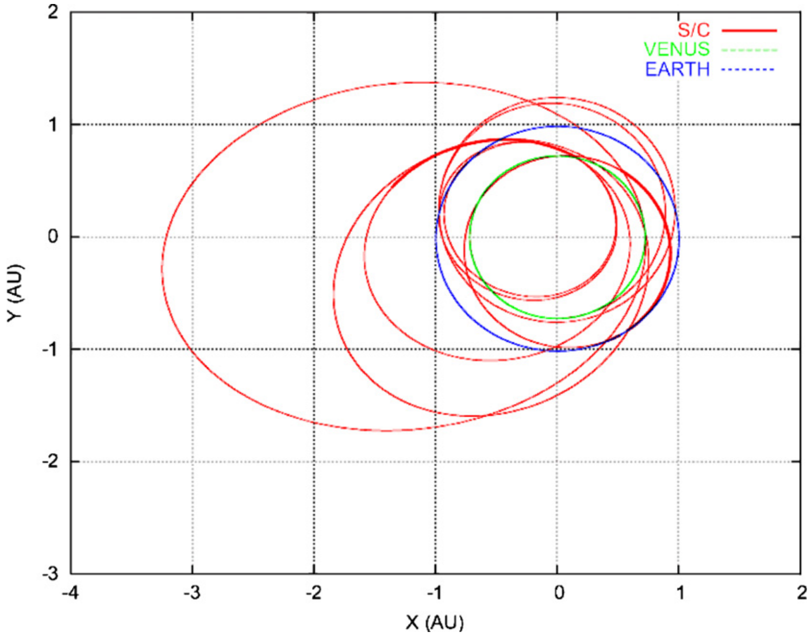

Fig. 9. Projection of the tour with swingbys at Earth and Venus (solution F).

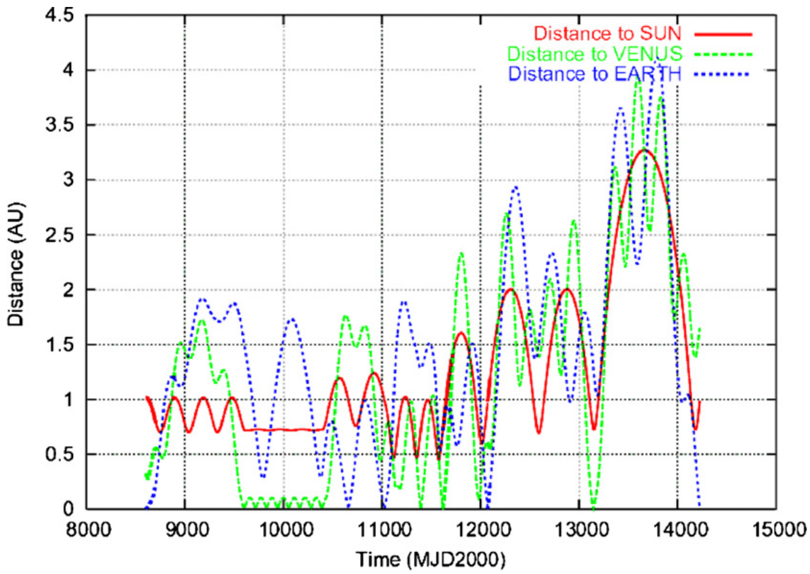

Fig. 10. Distance to the main bodies in the inner tour (solution F).

after E_4. The first delta-V is too high to be implemented by just one arc, and it is then split into two thrust arcs, as there is time enough until reaching Venus. The second and the third manoeuvre are implemented without inconvenience, whereas the fourth manoeuvre ends up filling almost all the interval between Earth and Jupiter (almost doubling the required delta-V). The final obtained cost function for this case is: $1.819872 \times 10^6\ \mathrm{kg\,km^2/s^2}$. The value is quite high, but still it differs from the ballistic value of $1.878 \times 10^6\ \mathrm{kg\,km^2/s^2}$ presented in Table 1 mainly due to the increased mass consumption required by the low-thrust performance. The duration of the whole mission is 28.331 years, slightly lower than the limit imposed.

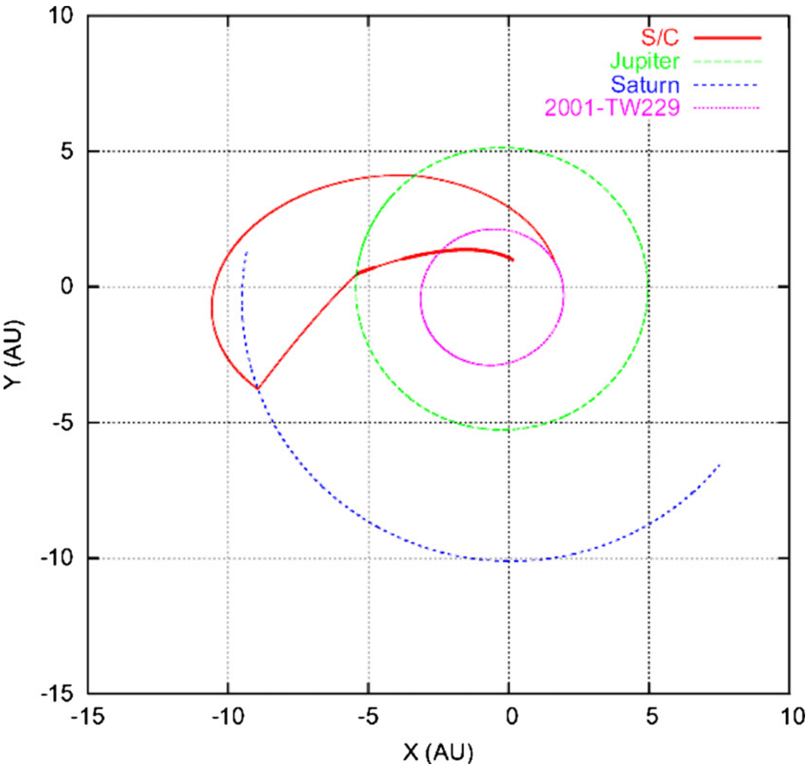

Fig. 11. Projection of the outer tour with swingbys at Earth, Jupiter and Saturn (solution F). *Note*: Do observe the final retrograde motion of the S/C after the swingby at Saturn and the double Jupiter swingby.

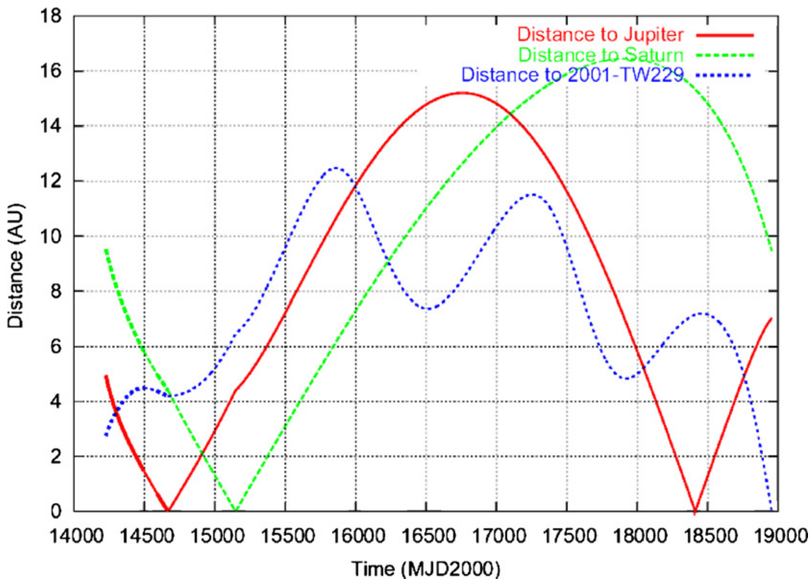

Fig. 12. Distance to the main bodies in the outer tour (solution F).

Figs. 9 and 10 present the results of the inner tour as done for the case of the solution E. In this solution the trajectory profile is more complicated than the previous and a large number of revolutions about the Sun are present. Again, the thrust arcs are represented by thicker lines.

Table 4
Reference values at the main trajectory events for case F

Event date	Main event	Thrust switch	Arcs	Duration (days)
Departure	27/07/2023 02:28:54	On	Thrust	99.6334
Thrust switch	03/11/2023 17:41:04	Off	Coast	178.9369
Thrust switch	30/04/2024 16:10:09	On	Thrust	8.7429
Thrust switch	09/05/2024 09:59:59	Off	Coast	709.5614
Venus swingby	18/04/2026 23:28:28	–	Coast	786.4012
Venus swingby	13/06/2028 09:06:11	–	Coast	268.4548
Earth swingby	08/03/2029 20:01:04	–	Coast	365.2569
Earth swingby	09/03/2030 02:11:00	–	Coast	369.8145
Venus swingby	13/03/2031 21:43:53	–	Coast	224.6861
Venus swingby	24/10/2031 14:11:48	On	Thrust	101.6304
Thrust switch	03/02/2032 05:19:37	Off	Coast	350.2008
Earth swingby	18/01/2033 10:08:46	On	Thrust	25.2106
Thrust switch	12/02/2033 15:11:58	Off	Coast	1049.9888
Venus swingby	29/12/2035 14:55:47	–	Coast	1077.9008
Earth swingby	11/12/2038 12:32:53	On	Thrust	270.6803
Thrust switch	08/09/2039 04:52:31	Off	Coast	96.3831
Thrust switch	13/12/2039 14:04:15	On	Thrust	76.1329
Jupiter swingby	27/02/2040 17:15:38	Off	Coast	480.1008
Saturn swingby	21/06/2041 19:40:46	–	Coast	3264.543
Jupiter swingby	30/05/2050 8:43:00	–	Coast	543.769
Asteroid swingby	25/11/2051 3:10:10	–	End	–

Table 5
Reference values at the planetary swingbys (solution F)

	Epoch (MJD2000)	S/C Mass (Kg)	Arrival velocity in J2000.0				Flyby radius (km)
			X-component (km/s)	Y-component (km/s)	Z-component (km/s)	Modulus (km/s)	
Departure	8608.103	1500.00	−2.07121	−1.39994	0.01536	2.50000	–
Venus	9604.978	1484.73	−2.59989	−1.72014	−3.76357	4.88700	15145.4
Venus	10391.379	1484.73	−0.06323	−2.51365	4.17442	4.87321	10975.0
Earth	10659.834	1484.73	7.72117	0.08648	−0.40024	7.73202	154408.8
Earth	11025.091	1484.73	7.66688	−0.48858	−0.65798	7.71056	11055.5
Venus	11394.906	1484.73	5.04346	12.43314	3.12243	13.77566	88852.1
Venus	11619.592	1484.73	5.51672	12.23761	3.01919	13.75895	6351.0
Earth	12071.423	1470.40	−4.79219	12.20541	5.28545	14.13765	16067.1
Venus	13146.622	1466.85	−7.49181	6.31790	1.33294	9.89039	6351.0
Earth	14224.523	1466.85	0.55171	14.72547	8.48581	17.00449	6678.0
Jupiter	14667.719	1414.04	−12.92630	6.02128	2.83227	14.53846	1160179.1
Saturn	15147.820	1444.27	−14.09410	−5.81645	−1.44151	15.31511	91422.7
Jupiter	18412.363	1444.27	24.19054	6.54639	1.97190	25.13813	10483338.1
Asteroid	18956.132	1444.27	−11.98666	19.75972	8.09625	24.48828	–

Figs. 11 and 12 present the results for the outer tour from the last Earth swingby to the impact on the asteroid. An interesting Jupiter–Saturn–Jupiter sequence allows improving the cost function even a bit more than in the previous case.

Table 4 provides the mission timeline and the main events occurring along the mission in the proposed profile. Finally, Table 5 presents the main values of interest in the swingbys for the whole trajectory profile (in the first line the "arrival velocity" concept refers in fact to the Earth escape velocity).

5. Conclusions

A number of relevant conclusion are highlighted in the following:

- DEIMOS Space has provided a Mission Analysis study on the possibilities to impact with a large momentum the given asteroid and complying with the imposed constraints and the tight schedule. The solutions found are very much performing.

- A systematic approach to the attainment of the best solutions in a global perspective has been successfully put to practice with a very efficient and successful result.
- Full families of feasible solutions were obtained providing a thorough insight in the structure and casuistic of the solution space.
- A dedicated analysis was performed on the most prominent cases, providing a full low-thrust optimisation on the most relevant scenarios.
- Solution E presents a cost function of $1.789510 \times 10^6\,\mathrm{kg\,km^2/s^2}$ which represents an exceptional case with retrograde arrival at the asteroid. The mission duration is 29.627 years.
- Solution F, presents an even better cost function of $1.819872 \times 10^6\,\mathrm{kg\,km^2/s^2}$ with also a retrograde arrival at the comet. The mission duration is 28.331 years.

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