GTOC 7: Solution from the ACT/ISAS team

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Abstract

This document is submitted in partial fullfillment of the requirements for an entry in the 7th Global Trajectory Optimization (GTOC 7) problem. It contains a description of the trajectory found by the ACT/ISAS team, a collaboration between the European Space Agency's Advanced Concepts Team and JAXA's Institute of Space and Astronautical Science.

1 Approach

We tackle the GTOC 7 problem in three phases:

First, we search for individual probe sequences of maximal length. We developed a variaton of a breadth-first tree search with limited frontier expansion and node ranking using adaptive weighting of mass and time. The "adaptive weighting" scheme is achieved by several techniques based on Pareto optimality and adaptive aggregate objective functions. At each step, the tree only branches towards "close" asteroids. We define "close" by first ranking all possible target astoids by a k-NN filter (i.e., the k nearest neighbours in the $\mathbf{r}$, $\mathbf{v}$ space). The filter is refined by computing the Lambert ΔV for each target asteroid within a certain distance. The branches are computed solving the optimal control problem for the low-thrust propulsion of the probe. Time-optimal and mass-optimal trajectories are considered as well as a few intermediate options. The initial starting epoch and asteroid for the root node of the tree searches are selected by targeting dense asteroid clusters computed by the DBSCAN algorithm.

Second, the longest asteroid sequences found (i.e., of length 13 and 14) are then patched to create a scenario for the mother spacecraft. The patching is accomplished by optimizing the full mother trajectory constrained to the release and collection points of the first probe mission. Evolutionary optimization techniques are combined with a similar tree search as outlined above to compute patching possibilities.

Finally, having one probe and the mother spacecraft scenario built, we search for trajectories for the other two probes by using the same initial tree search method, modified with a targeting technique and an asteroid tabu list. These modifications ensure that the second and third probe will target possible collection points along the mother spacecraft orbit while avoiding randevouz with already visited asteroids on their way.

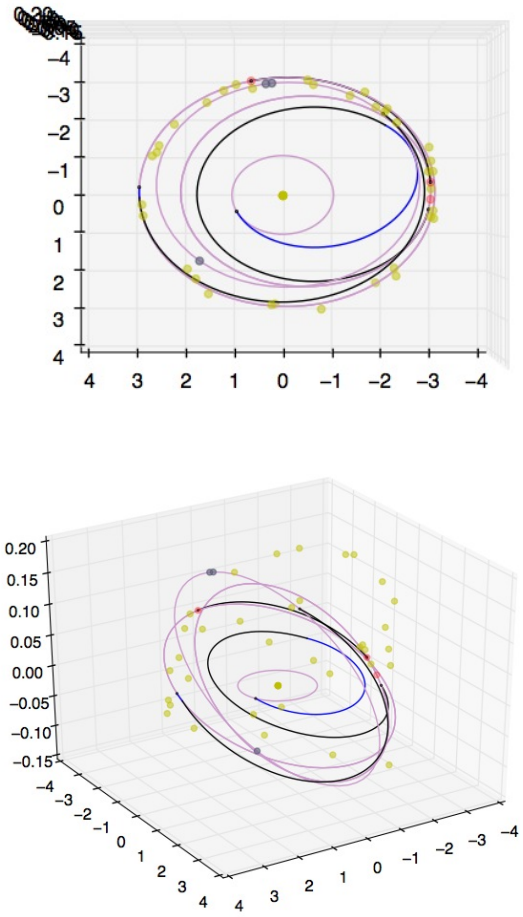

Figure 1: View of the mother spacecraft trajectory. Collection and release points are visualized as red and blue dots, asteroid visited by the daughters are visualized as yellow dots (randevouz positions are reported)

2 The best trajectory found: Jaqen H'ghar

Named after a character of the popular TV series "Game of Thrones" we computed that our submission achieves a primary score $J = 35$ and a secondary score $J_0 = 2502.167$ kg. At the launch of the mothership from Earth $V_\infty = 6$ km/s. At the end of the trajectory when the last probe is recollected the final mass of the mother ship is $M_f = 8795.0$ kg.

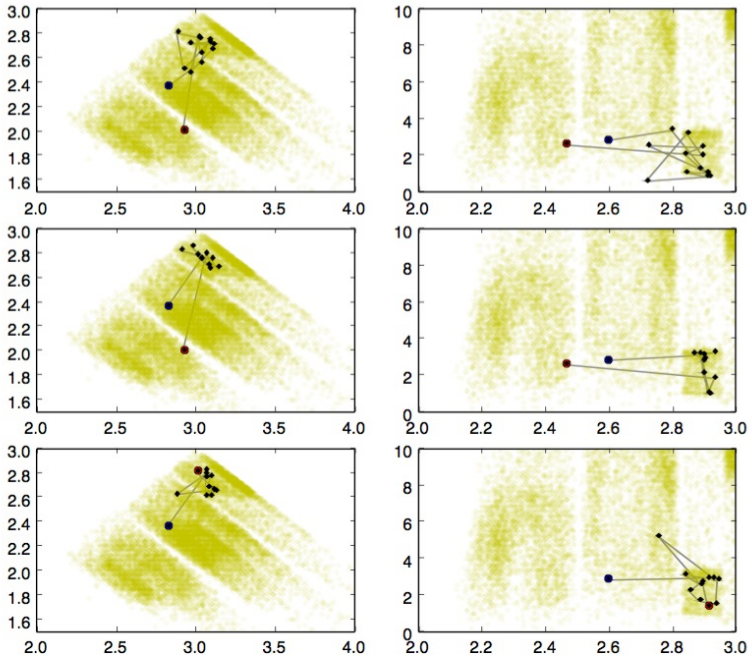

Figure 2: Visualization of the orbital parameters of the asteroids visited by the three probes overlapped with the background asteroid population. Starting asteroid is visualized as a red dot, final asteroid is visualized as a blue dot. Background population is reported in yellow.

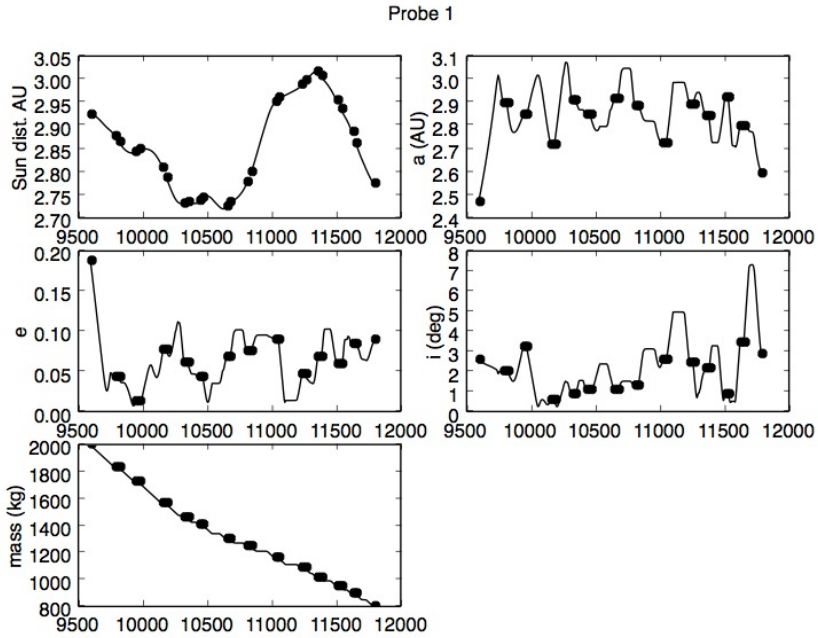

Figure 3: Probe 1 trajectory analysis

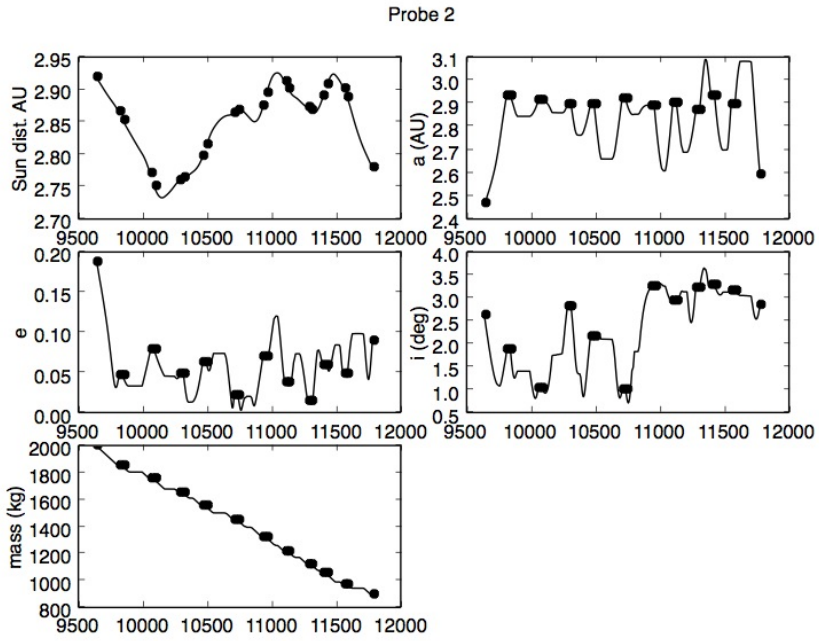

Figure 4: Probe 2 trajectory analysis

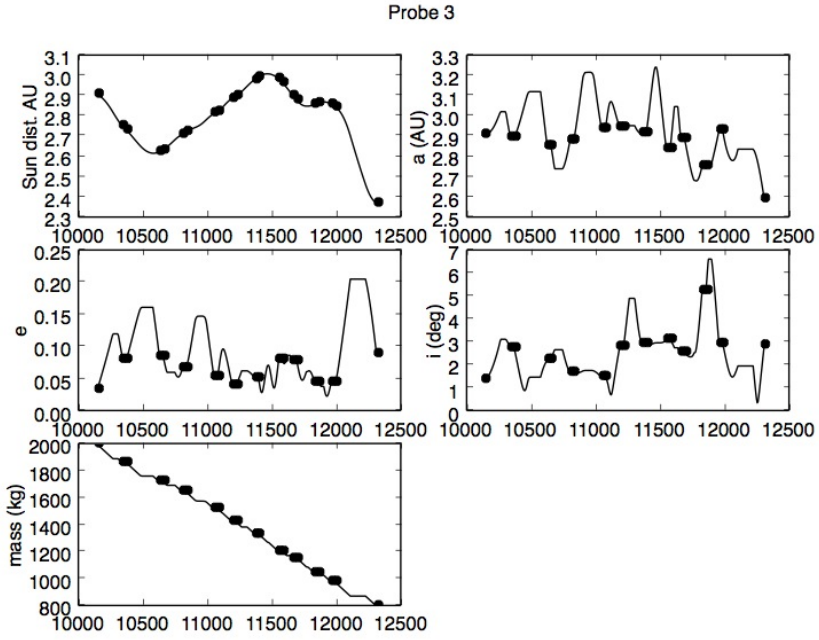

Figure 5: Probe 3 trajectory analysis

3 Mission timeline

	Event	Mission time	Probe time	
*	Mother : Earth departure	59483.87	0.00y	0.00y
*	Mother : Arrival at #5318	61144.61	4.55y	
-	Probe 1: Release	61144.61	4.55y	0.00y
-|-	Probe 2: Release	61162.69	4.60y	0.00y
* | |	Mother : Departure from #5318 (Gregory)	61162.69	4.60y	
| | *	Probe 2: Departure from #5318 (Gregory)	61192.69	4.68y	0.08y
| * |	Probe 1: Arrival at #3916 (Akkado)	61336.68	5.07y	0.53y
| | *	Probe 2: Arrival at #14254 (1998 SE130)	61362.72	5.14y	0.55y
| * |	Probe 1: Departure from #3916 (Akkado)	61366.68	5.15y	0.61y
| | *	Probe 2: Departure from #14254 (1998 SE130)	61392.72	5.23y	0.63y
| * |	Probe 1: Arrival at #1138 (Hamiltonia)	61490.07	5.49y	0.95y
| * |	Probe 1: Departure from #1138 (Hamiltonia)	61520.07	5.57y	1.03y
| | *	Probe 2: Arrival at #7422 (1993 RY11)	61605.00	5.81y	1.21y
| | *	Probe 2: Departure from #7422 (1993 RY11)	61635.00	5.89y	1.29y
* | |	Mother : Arrival at #11048 (1998 QV37)	61658.90	5.95y	
-|-|-	Probe 3: Release	61658.90	5.95y	0.00y
| | | *	Probe 3: Departure from #11048 (1998 QV37)	61688.90	6.04y	0.08y
| * | |	Probe 1: Arrival at #13907 (1997 VD3)	61703.29	6.08y	1.53y
| * | |	Probe 1: Departure from #13907 (1997 VD3)	61733.29	6.16y	1.61y
| | * |	Probe 2: Arrival at #5028 (Musschenbroek)	61837.96	6.45y	1.85y
| * | |	Probe 1: Arrival at #2343 (Fedchenko)	61865.25	6.52y	1.97y
| | * |	Probe 2: Departure from #5028 (Musschenbroek)	61867.96	6.53y	1.93y
| | | *	Probe 3: Arrival at #12530 (1994 UO)	61870.86	6.54y	0.58y
| * | |	Probe 1: Departure from #2343 (Fedchenko)	61895.25	6.60y	2.06y
| | | *	Probe 3: Departure from #12530 (1994 UO)	61900.86	6.62y	0.66y
* | | |	Mother : Departure from #11048 (1998 QV37)	61905.15	6.63y	
| * | |	Probe 1: Arrival at #6519 (1999 RU16)	61982.97	6.84y	2.30y
| | * |	Probe 2: Arrival at #2339 (Drunina)	62012.66	6.92y	2.33y
| * | |	Probe 1: Departure from #6519 (1999 RU16)	62012.97	6.92y	2.38y
| | * |	Probe 2: Departure from #2339 (Drunina)	62042.66	7.01y	2.41y
| | | *	Probe 3: Arrival at #12478 (1999 RA87)	62122.12	7.22y	1.27y
| | | *	Probe 3: Departure from #12478 (1999 RA87)	62152.12	7.31y	1.35y
| * | |	Probe 1: Arrival at #11046 (1978 RL7)	62197.42	7.43y	2.88y
| * | |	Probe 1: Departure from #11046 (1978 RL7)	62227.42	7.51y	2.96y
| | * |	Probe 2: Arrival at #7428 (Takihiroi)	62252.05	7.58y	2.98y
| | * |	Probe 2: Departure from #7428 (Takihiroi)	62282.05	7.66y	3.06y
| | | *	Probe 3: Arrival at #12514 (1999 VW49)	62323.48	7.77y	1.82y
| | | *	Probe 3: Departure from #12514 (1999 VW49)	62353.48	7.86y	1.90y
| * | |	Probe 1: Arrival at #447 (Dresda)	62355.86	7.86y	3.32y
| * | |	Probe 1: Departure from #447 (Dresda)	62385.86	7.95y	3.40y
| | * |	Probe 2: Arrival at #16008 (Rios)	62477.71	8.20y	3.60y
| | * |	Probe 2: Departure from #16008 (Rios)	62507.71	8.28y	3.68y
| | | *	Probe 3: Arrival at #16067 (Hennigar)	62558.63	8.42y	2.46y
| * | |	Probe 1: Arrival at #4903 (Le Creusot)	62568.63	8.45y	3.90y
| | | *	Probe 3: Departure from #16067 (Hennigar)	62588.63	8.50y	2.55y
| * | |	Probe 1: Departure from #4903 (Le Creusot)	62598.63	8.53y	3.98y
| | * |	Probe 2: Arrival at #1896 (Birkle)	62649.32	8.67y	4.07y
| | * |	Probe 2: Departure from #1896 (Birkle)	62679.32	8.75y	4.15y
| * | |	Probe 1: Arrival at #14212 (1998 OG9)	62776.65	9.02y	4.47y
| | | *	Probe 3: Arrival at #6567 (Ockels)	62802.04	9.08y	3.13y

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| * | |  Probe 1: Departure from #14212 (1998 OG9)                  62806.65  9.10y  4.55y
| | * |  Probe 2: Arrival at #5717 (1995 YP)                       62826.56  9.15y  4.56y
| | | *  Probe 3: Departure from #6567 (Ockels)                    62832.04  9.17y  3.21y
| | * |  Probe 2: Departure from #5717 (1995 YP)                   62856.56  9.23y  4.64y
| * | |  Probe 1: Arrival at #8428 (1999 RW41)                     62902.16  9.36y  4.81y
| * | |  Probe 1: Departure from #8428 (1999 RW41)                 62932.16  9.44y  4.89y
| | * |  Probe 2: Arrival at #16062 (1998 RA78)                    62944.77  9.48y  4.88y
| | | *  Probe 3: Arrival at #5764 (Foglia)                        62974.46  9.56y  3.60y
| | * |  Probe 2: Departure from #16062 (1998 RA78)                62974.77  9.56y  4.96y
| | | *  Probe 3: Departure from #5764 (Foglia)                    63004.46  9.64y  3.68y
| * | |  Probe 1: Arrival at #11055 (Takeda)                       63052.48  9.77y  5.22y
| * | |  Probe 1: Departure from #11055 (Takeda)                   63082.48  9.85y  5.31y
| | * |  Probe 2: Arrival at #12536 (1998 QL44)                    63101.99  9.91y  5.31y
| | | *  Probe 3: Arrival at #4394 (1992 EC4)                      63102.56  9.91y  3.95y
* | | |  Mother : Arrival at #10449 (1999 RO63)                    63116.71  9.95y
| | * |  Probe 2: Departure from #12536 (1998 QL44)                63131.99  9.99y  5.39y
| | | *  Probe 3: Departure from #4394 (1992 EC4)                  63132.56  9.99y  4.03y
| * | |  Probe 1: Arrival at #7346 (1998 HK17)                     63170.44 10.09y  5.55y
| * | |  Probe 1: Departure from #7346 (1998 HK17)                 63200.44 10.18y  5.63y
| | | *  Probe 3: Arrival at #2654 (1998 QP47)                     63212.88 10.21y  4.25y
| | | *  Probe 3: Departure from #2654 (1998 QP47)                 63242.88 10.29y  4.34y
| | * |  Probe 2: Arrival at #10449 (1999 RO63)                    63324.19 10.51y  5.92y
*-* | |  Probe 1: Return                                           63336.11 10.55y  6.00y
*---* |  Probe 2: Return                                           63354.19 10.60y  6.00y
|     *  Probe 3: Arrival at #7292 (Goerdeler)                     63374.77 10.65y  4.70y
|     *  Probe 3: Departure from #7292 (Goerdeler)                 63404.77 10.73y  4.78y
|     *  Probe 3: Arrival at #4450 (Robinwilliams)                 63505.53 11.01y  5.06y
|     *  Probe 3: Departure from #4450 (Robinwilliams)             63535.53 11.09y  5.14y
|     *  Probe 3: Arrival at #10449 (1999 RO63)                   63850.40 11.95y  6.00y
*-----*  Probe 3: Return                                           63850.40 11.95y  6.00y
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