Team 19 Response to the
7^{th} Global Trajectory Optimisation Competition
hosted by
Politecnico di Torino and Università di Roma, La Sapienza
May-June 2014

Team 19 - JPL

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17 June 2014

Broad Search

Several broad search strategies were considered. These were coupled with three guiding philosophies. First, the one relied on most heavily, was the creation of 'long-chain backbones,' that is, long sequences of asteroid rendezvous by one probe. The Mothership and other probe trajectories were then built up, in that order, based on the long-chain backbone. The second and lesser used approach was to design first Mothership trajectories, a 'Mothership backbone,' wherein the mother would drop-off probes at a series of asteroids, followed by probe trajectories starting at these asteroids and returning to the mother at a final asteroid. The third philosophy was that all of these chains would be initially designed assuming the Mothership would rendezvous with asteroids for probe pick-up and drop-off. Once good candidates were found, this assumption was lifted and separation and rejoining of mother and probes was permitted to occur away from asteroids in order to boost the mass performance and the asteroid count.

Various approaches were taken in building the long-chain backbones and the Mothership backbones. The most promising that we found was based on combinatorial analyses of Lambert solutions, dubbed 'STAR' by the developer of the method at JPL. In the STAR approach, a grid is made for the times at the various bodies, and all Lambert solutions are computed between the bodies, subject to v_∞ and flight-time constraints. Then the Lambert fits are combined to form an end-to-end impulsive trajectory. At each combinatorial step, the combinations are iteratively pruned by a variety of criteria, such as ΔV, flight time, and asteroids visited, to avoid an explosion in the number of combinations that must be carried forward. The promising chains were then passed to a local optimiser for propellant mass optimisation.

Another approach was to build up chains, one asteroid at a time, pruning and adjusting weighting factors as the chain grew, but with attention to retaining diversity. Candidate asteroids to be added were selected based on Lambert-arc ΔV and on the phase-free proximity quotients Q and he. The candidates would then be passed to the local optimiser, whereafter a screened subset of the converged solutions would be retained for the next step. This approach was slower and less effective than the STAR approach, probably due to the relatively high thrust level which allowed short transfer arcs to arise and be reasonably well modelled by Lambert arcs.

Ant colony optimisation, particle swarm optimisation, and genetic algorithms were also used for chain-building. These methods also used Lambert-arc ΔV and Q and he to find long chains. The methods sought chains of a fixed length, iteratively selecting, retaining, and recombining sub-chains as the 'free variables' or 'particles'. The better chains were again passed to a local optimiser.

Close approaches were also studied as a possible filter for finding chains of asteroids. A database of close approaches for all asteroids over the entire date window was created and studied for chains of close approaches. Similarly, some thought was given to identifying time-varying regions of high asteroid density.

Clustering techniques based on Q and he were also studied to identify sub-groups of asteroids that might be searched for long chains or whose centroids might be used when following the Mothership backbone philosophy.

Building up Trajectory Quartets

Focussing on the long-chain backbone method, Mothership trajectories were added to the backbone, first using very rapid Lambert-arc computations, and subsequently, for the more promising cases, with the local optimiser MALTO (see below). Thereafter, chains for the second and third Probe were added in using the methods described above. At this stage, the best candidates were relieved of the constraint that pick-up and drop-off must occur at an asteroid, and numerous variations were sought on the chains.

Local Optimisation and Refinement of Trajectory Quartets as a Whole

The local optimiser used for individual trajectories was primarily MALTO (as in previous GTOCs), which models the low thrust as a series of small impulses, whose direction and magnitude are to be optimised using a non-linear programming method (SNOPT). The initial guesses from the broad search were optimised in MALTO, with the most promising candidates further refined by hand. For example, MALTO cannot automatically add bodies and so this type of refinement was done out-of-the-loop, insofar as time permitted.

Very importantly, a direct optimiser was also written very hastily and applied to the full trajectory quartet problem as a whole. This, as mentioned above, allowed significant freedom in choosing initial and final asteroids, and also freed up propellant mass on the daughter craft to enable a larger number of asteroids to be visited.

Submitted solution

Our best solution is shown in the tables and in the figures. It visits 36 different asteroids (primary objective). The sum of the Probe masses at the end of the mission is 2450.257 kg (secondary objective). That is:

$$\begin{aligned} J &= 36 \\ J' &= 2450.257\ \mathrm{kg} \end{aligned}$$

Thank You to the Organisers

We found this year's competition exciting and thought provoking. It was a well-conceived and well-balanced problem that generated many ideas and conversations during this past month. Many thanks for hosting this edition of the competition.

Table 1: **Mothership Trajectory**

Event	Date (yyyy-mm-dd)	TOF (days)	$v_\infty/\Delta V$ (km/s)	Mass after event (kg)	Cumulative Mprop (kg)
Launch	2024-04-12	0.00	6.000	24000.00	0.00
DV 1	2024-06-09	57.63	0.956	21536.82	2463.18
DV 2	2025-09-08	513.86	4.558	12849.61	11150.39
Release of probe 2	2027-02-15	1038.03	0.000	10849.61	11150.39
DV 3	2027-02-15	1038.09	0.045	10793.99	11206.01
Release of probe 1	2028-03-14	1431.98	0.000	8793.99	11206.01
DV 4	2028-03-14	1431.98	0.017	8776.72	11223.28
Release of probe 3	2028-05-29	1507.91	0.000	6776.72	11223.28
DV 5	2028-07-09	1548.78	0.197	6626.77	11373.23
DV 6	2032-03-29	2907.87	0.468	6284.39	11715.61
Return of probe 2	2033-02-14	3229.47	0.000	7111.01	11715.61
DV 7	2033-06-03	3338.33	0.142	6997.89	11828.73
DV 8	2034-02-24	3604.60	0.184	6853.78	11972.84
Return of probe 1	2034-03-15	3623.42	0.000	7670.71	11972.84
Return of probe 3	2034-05-30	3699.35	0.000	8477.42	11972.84

Table 2: **Probe 1 Trajectory — 12 Asteroids**

Event/Ast	Date (yyyy-mm-dd)	TOF (days)	Stay (km/s)	Mass after event (kg)
Dep. Mother	2028-03-14	0.00	0.00	2000.00
14101	2028-08-04	142.05	30.00	1878.57
10973	2029-02-22	344.27	30.00	1782.43
2346	2029-08-26	529.21	30.00	1675.42
10992	2030-01-11	667.63	30.00	1593.82
438	2030-07-20	857.21	30.00	1453.22
1399	2030-12-17	1007.05	30.00	1347.62
3884	2031-04-02	1113.65	30.00	1289.91
2332	2031-09-30	1294.14	30.00	1185.75
15548	2032-07-18	1586.74	30.00	1006.54
12111	2032-11-12	1703.21	30.00	948.29
3411	2033-02-25	1808.23	30.00	888.72
13844	2033-10-25	2050.84	30.00	847.52
Rejoin Mother	2034-03-15	2191.44	0.00	816.93

Table 3: **Probe 2 Trajectory — 13 asteroids**

Event/Ast	Date (yyyy-mm-dd)	TOF (days)	Stay (km/s)	Mass after event (kg)
Dep. Mother	2027-02-15	0.00	0.00	2000.00
7411	2027-02-20	5.68	30.00	1995.45
4407	2027-07-29	164.12	30.00	1899.77
3415	2028-03-05	384.07	30.00	1760.68
16038	2028-11-29	653.73	30.00	1596.86
14215	2029-04-22	797.16	30.00	1509.41
8456	2029-11-15	1004.91	30.00	1404.55
7405	2030-06-02	1203.35	30.00	1334.80
14225	2030-10-24	1347.06	30.00	1249.27
9661	2031-03-15	1489.97	30.00	1149.79
8494	2031-07-31	1627.16	30.00	1092.87
13722	2032-04-15	1886.22	30.00	976.93
3620	2032-09-16	2040.13	30.00	902.62
15853	2033-01-10	2156.85	33.35	827.71
Rejoin Mother	2033-02-14	2191.44	0.00	826.62

Table 4: **Probe 3 Trajectory — 11 asteroids**

Event/Ast	Date (yyyy-mm-dd)	TOF (days)	Stay (km/s)	Mass after event (kg)
Dep. Mother	2028-05-29	0.00	0.00	2000.00
5331	2028-12-06	190.32	30.00	1840.76
13899	2029-06-08	374.23	30.00	1705.15
1401	2029-12-03	552.37	30.00	1576.15
14158	2030-06-29	761.06	30.00	1481.65
10752	2031-01-12	957.54	30.00	1383.92
4396	2031-08-17	1174.17	30.00	1268.61
2345	2031-11-30	1279.96	30.00	1202.55
2324	2032-04-18	1419.79	30.00	1130.22
126	2032-09-08	1562.30	30.00	1043.32
1569	2033-04-26	1792.37	30.00	916.63
4990	2033-10-29	1978.51	30.00	855.92
Rejoin Mother	2034-05-30	2191.44	30.00	806.70

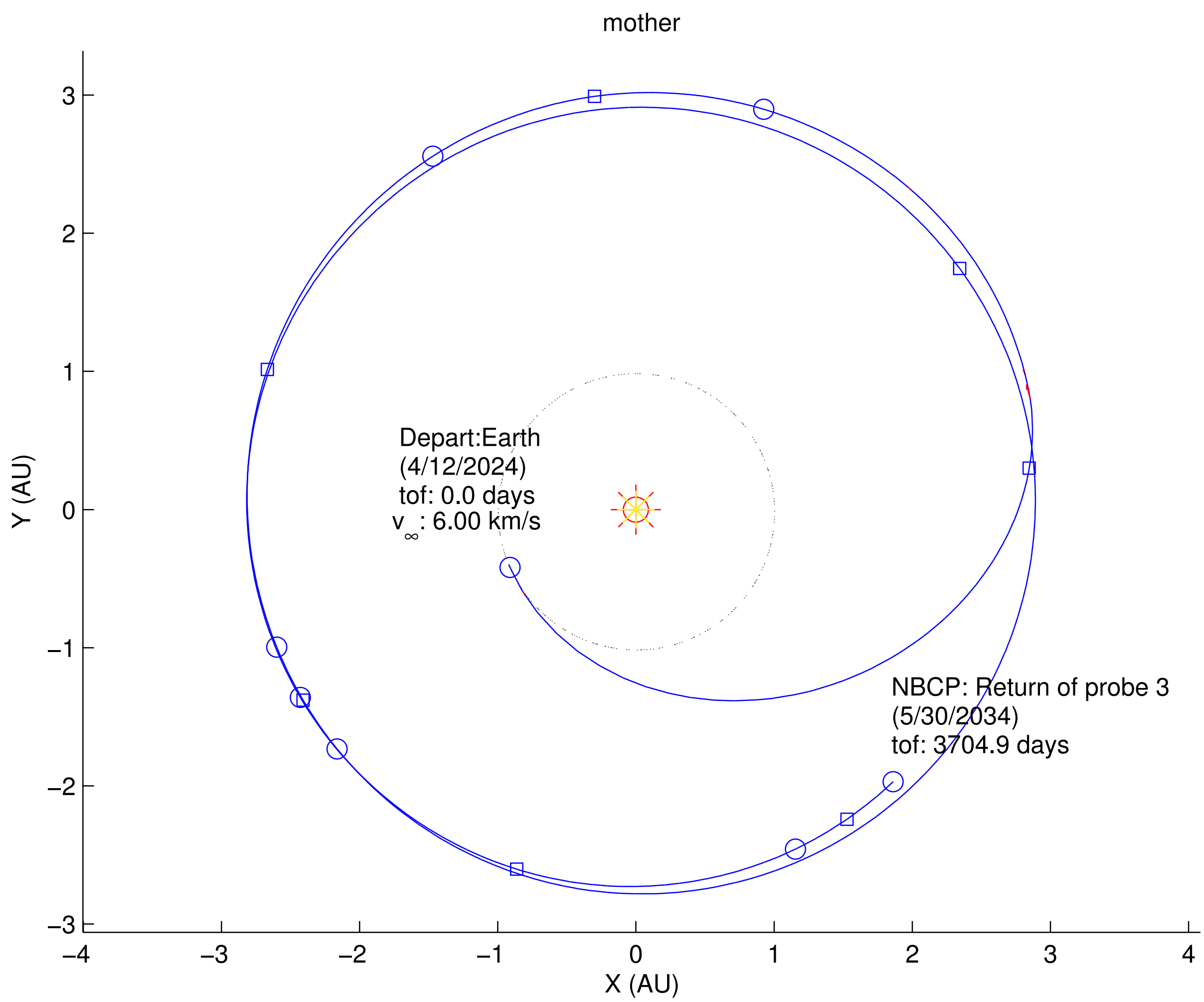

Figure 1: Mothership trajectory, projection onto the ecliptic of J2000.

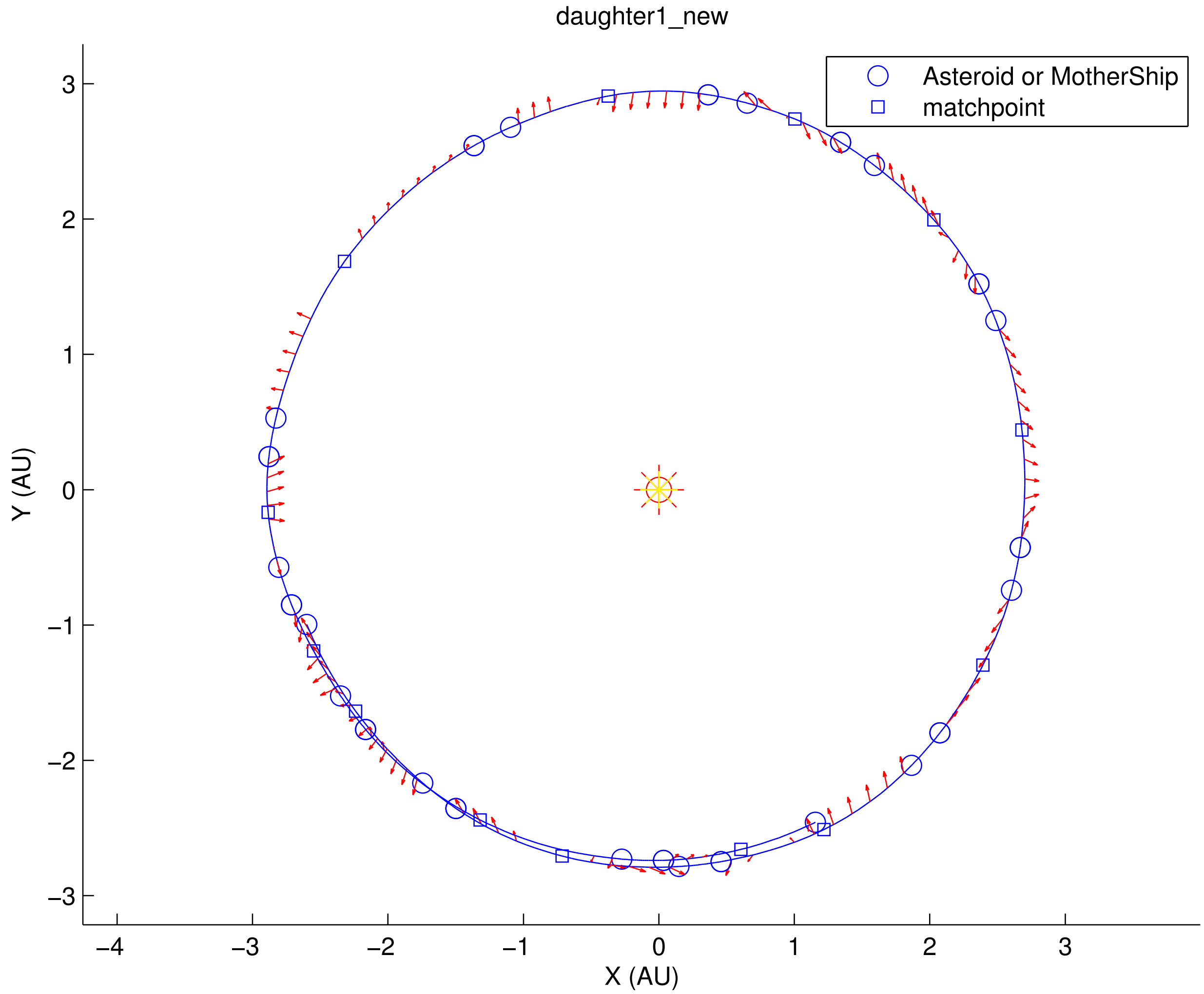

Figure 2: Probe 1 trajectory, projection onto the ecliptic of J2000.

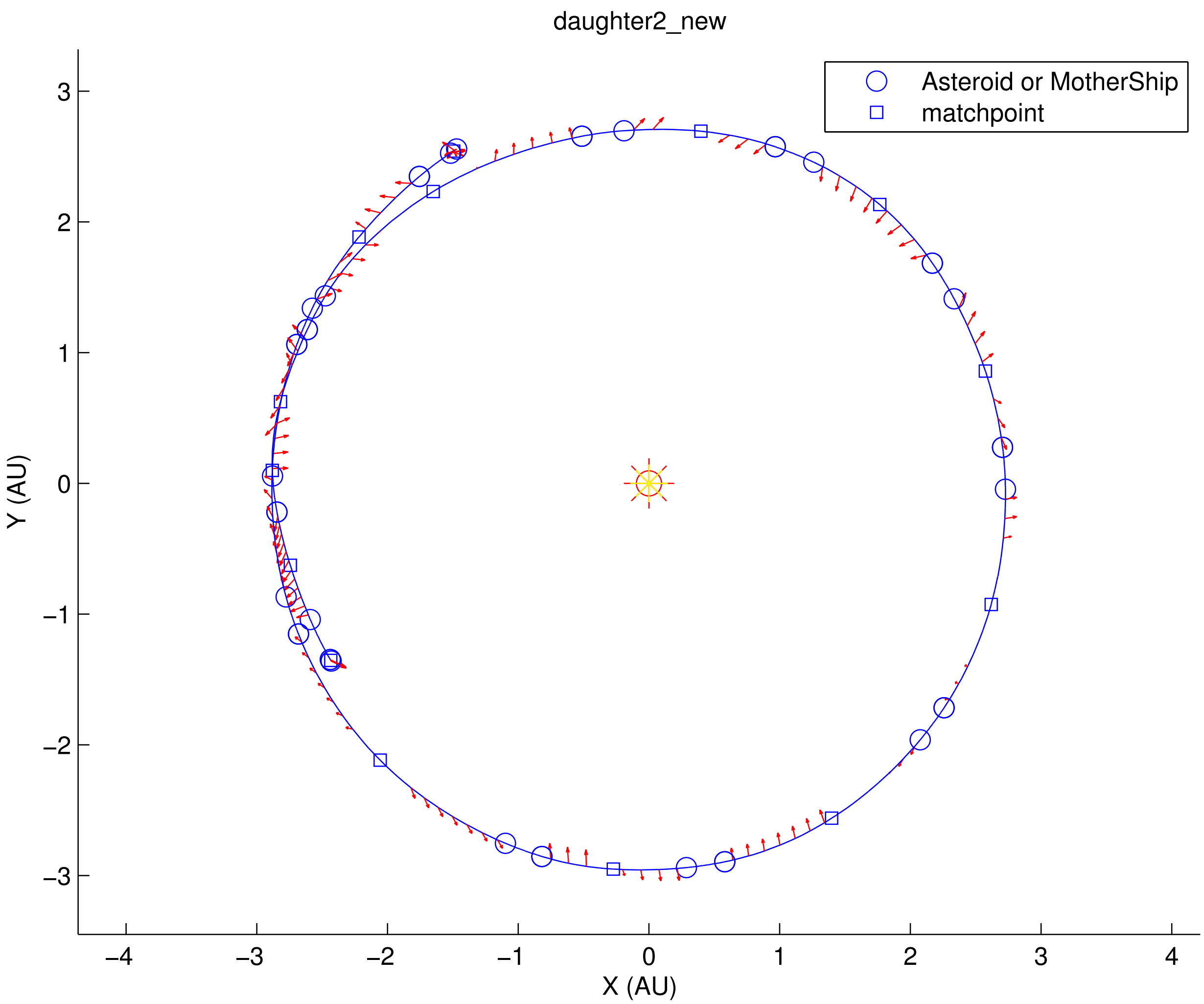

Figure 3: Probe 2 trajectory, projection onto the ecliptic of J2000.

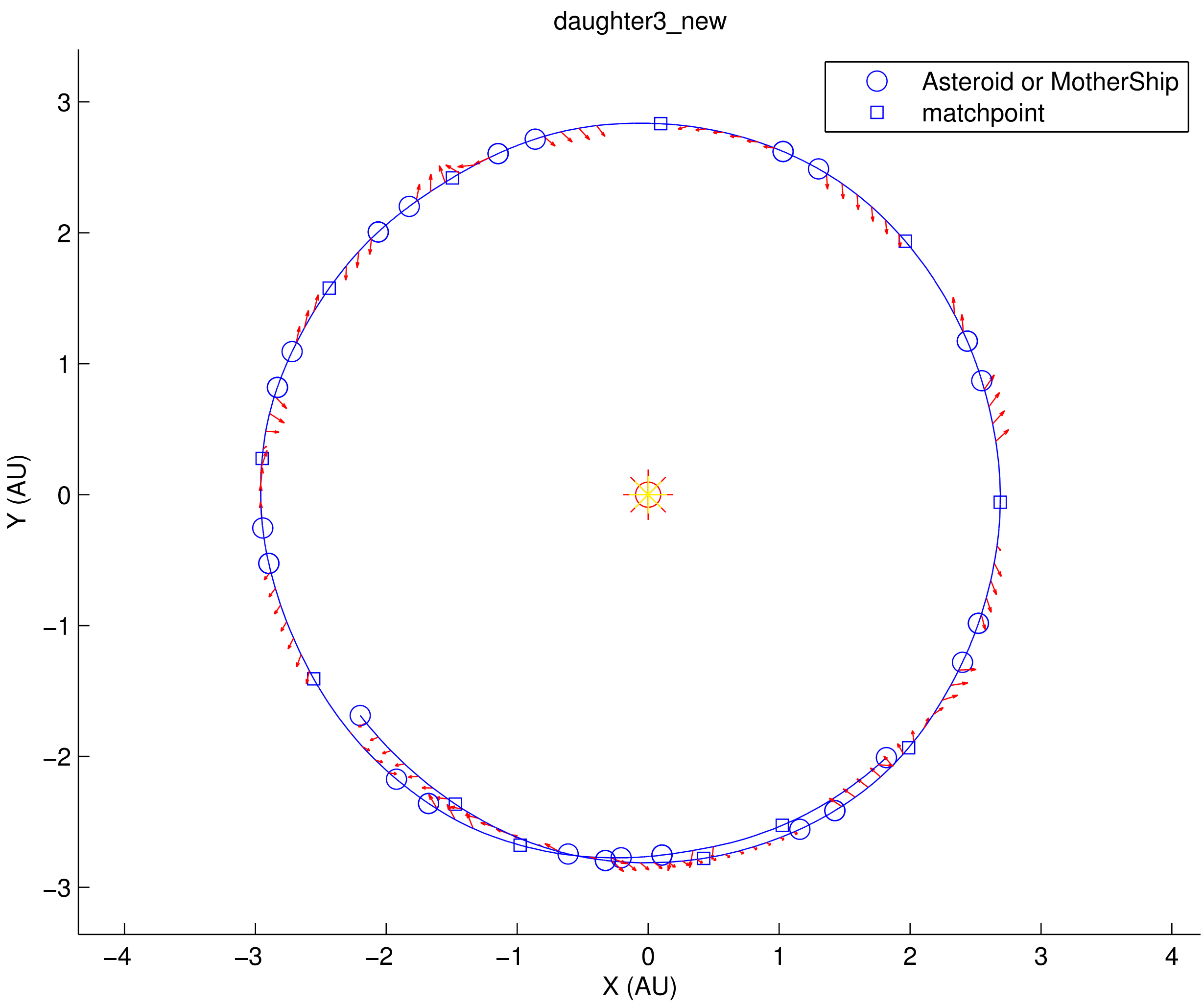

Figure 4: Probe 3 trajectory, projection onto the ecliptic of J2000.