CHOPIN: description (GTOC4)

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Methods

Initial Estimates

We first focussed our attention to what we felt was the hardest constraint to meet–the rendezvous with the final asteroid. Thus, potential candidates for the last asteroid were found by taking all asteroids from the set that have an orbit "similar" to that of Earth. Initial estimates for the launch and arrival date came from solving simple multi-revolution Lambert problems with 9, 10 or 11 full revolutions. Those combinations of launch and arrival dates that gave the lowest V_∞ at the asteroid in question, while satisfying the 4 km/s constraint on V_∞ at Earth, were used in the following analysis.

We set the spacecraft's initial state-vector equal to that of one of the asteroids at one of the dates thus found, so that the constraints regarding the final asteroid were inherently met. All positions were propagated backwards in time, from that initial date towards the launch date. Potential asteroid flybys were found by looking at the distance all asteroids had to the spacecraft's instantaneous Keplerian orbit, within a small time interval from the initial time. If some asteroids were found to be closer to the spacecraft's orbit than some threshold distance, we selected the one closest to Earth's orbit. If no asteroids were found to be close enough, we simply increased the length of the time interval and tried again.

Initially, these time intervals were set to 2 weeks, and were increased in steps of 2 weeks in case no asteroids were found. The threshold distance varied with time, and was based on the maximum change in orbital energy the ion engine could accomplish during the given time interval. In case an asteroid was selected for a flyby, we solved the exponential sinusoid Lambert-problem from the initial asteroid to the position of the potential flyby asteroid (see [Izzo, 2006]). This lambert-procedure involves a free design parameter (usually called k_2), which was optimized together with the transfer time, such that the impulsive velocity change required at the flybys was minimal. If that minimum ΔV was found to be larger than the maximum ΔV that could be achieved by the ion-engine during the transfer time to that asteroid, the asteroid was discarded and the procedure restarted.

This whole process is repeated until the total transfer time (from the last asteroid to the current asteroid) was about 9 years. After that time, we stopped looking for asteroids and focussed on going to Earth. This part of the trajectory was optimized using the same low-thrust Lambert-problem approach.

We found that the Earth was quite hard to reach for some final asteroids and initial rendezvous date combinations. Therefore, we simply tried all asteroids and rendezvous dates found initially, until we had a set that both had many asteroid flybys and a feasible Earth leg.

Optimization

For the final optimization, all positions are propagated forward in time again, from the launch date to the rendezvous date. Although the exponential sinusoids give good estimates for flyby candidates and transfer times, they are not so well suited to optimize these parameters. For that reason, we used the following method.

We found that fixing all positions to those values obtained by the exponential sinusoid approach made it quite hard to meet all the constraints, gave rather small end values for the mass and moreover, did not give convergence in many cases. For that reason, 2 legs were optimized simultaneously. That is, for each asteroid-asteroid leg, one additional asteroid was taken from the set, and the two connecting arcs were optimized for maximum end mass at the third asteroid. For each trio, the positions of the first and last asteroid were kept fixed, while the position of the central asteroid was allowed to vary. When the minimum mass was found while respecting the required 1 m/s accuracy in the velocity, the position of the central asteroid was fixed, the next asteroid from the set was added, the (optimized) velocity at the former central asteroid was added as a constraint, the position of the former third asteroid was released, and the next two legs were optimized (see Figure 1). Using this method, not only the final mass is optimized, but also the transfer times and positions of the flyby asteroids.

Because the constraints are different for the Earth leg and the leg to the rendezvous asteroid, these two legs were treated some what differently. For the Earth leg, the position of the *third* asteroid asteroid was kept fixed, while the central asteroid and the Earth were allowed to move. For the leg to the final rendezvous asteroid, only the position of the first asteroid was kept fixed, while the positions of the central asteroid and the rendezvous asteroid were allowed to vary. This proved somewhat easier to meet the (more strict) constraints on these two bodies, .i.e, the maximum allowed V_∞ of 4 km/s at Earth, and the requirement that $V_{rel} = 0$ at the rendezvous asteroid.

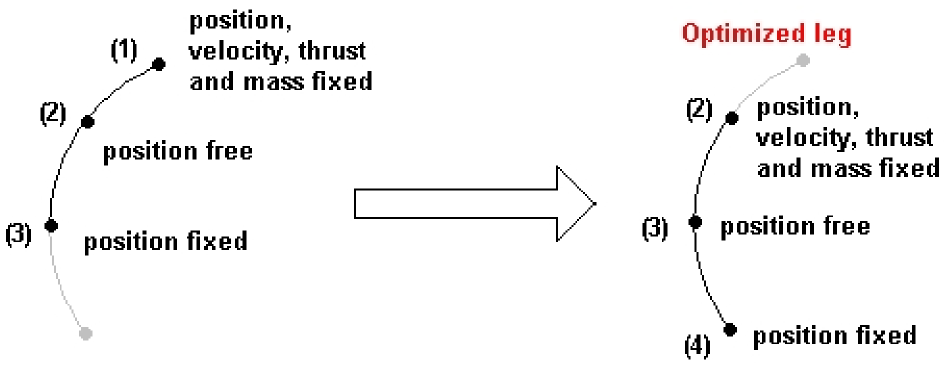

Figure 1: Method used in the final optimization. Each leg is optimized by optimizing the next leg simultaneously.

We tried a variety of optimization methods. The first one we tried was an indirect method, but that proved to be quite hard to apply to this problem. The second method, developed by [Sims and Flanagan, 1999], proved to be too time consuming, and had poor convergence properties. The only one we could get to converge in a reasonable time, was a combination of nonlinear programming and collocation (see [Hargraves and Paris, 1986]). Optimizing each set of initial estimates with this method required about 11 hours.

Results

A overview of the whole trajectory can be found in Figures 2 and 3. In these figures, the black dots represent asteroids, the blue dot the Earth, and the red dot the rendezvous asteroid. The mass variation over time is shown in Figure 4. All asteroids flown by, as well as the encounter dates, are listed in Table 1. All optimized values for this problem are:

Final rendezvous asteroid: 2008UA202

V_∞ **at Earth:** 3.995 km/s

Launch date: MJD 59857.4913

Number of asteroids flown by: 25

Final mass: 1436.4247 kg.

total time of flight: 10.1205 years.

Discussion

Note that the for the best result we obtained, the constraint on the maximum mission duration could not be met. More importantly, we could only get solutions to converge two days before the GTOC4 deadline, so that we did not have time to validate our final result. Judging by the thrust and mass profiles however (see Figure 5), our solution is probably prone to some errors, and can probably be improved.

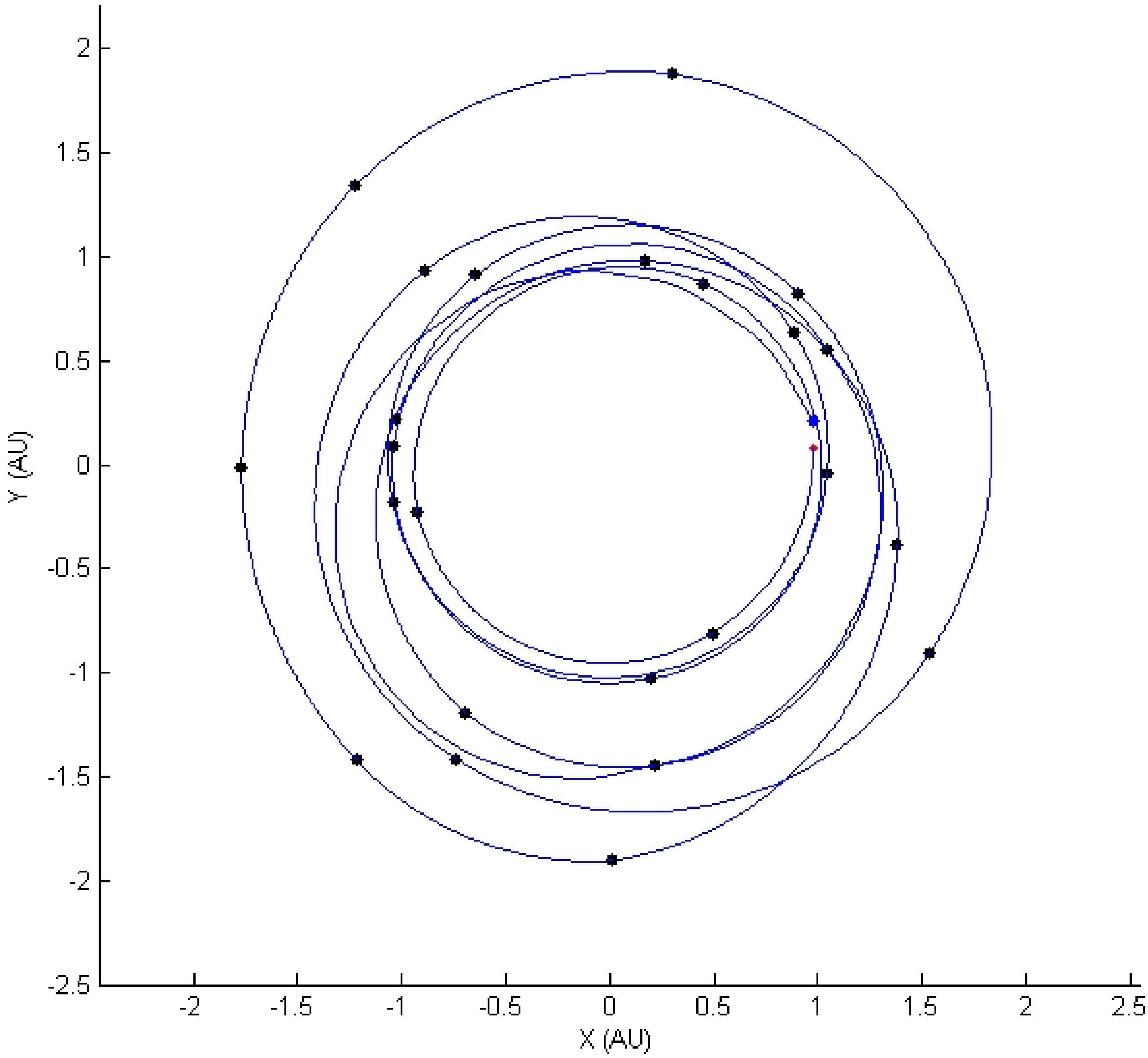

Figure 2: Projection of the trajectory onto the XY-plane. The black dots represent asteroids, the blue dot the Earth, and the red dot the rendezvous asteroid.

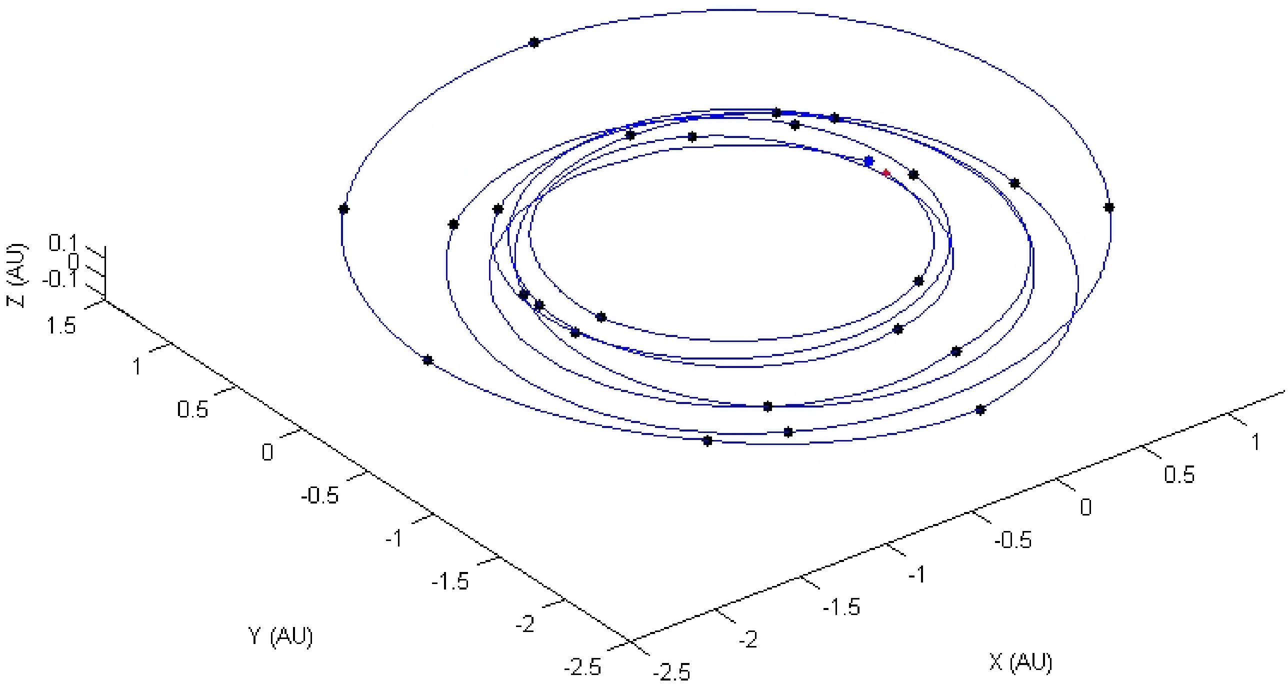

Figure 3: Three-dimensional view of the whole trajectory. The black dots represent asteroids, the blue dot the Earth, and the red dot the rendezvous asteroid.

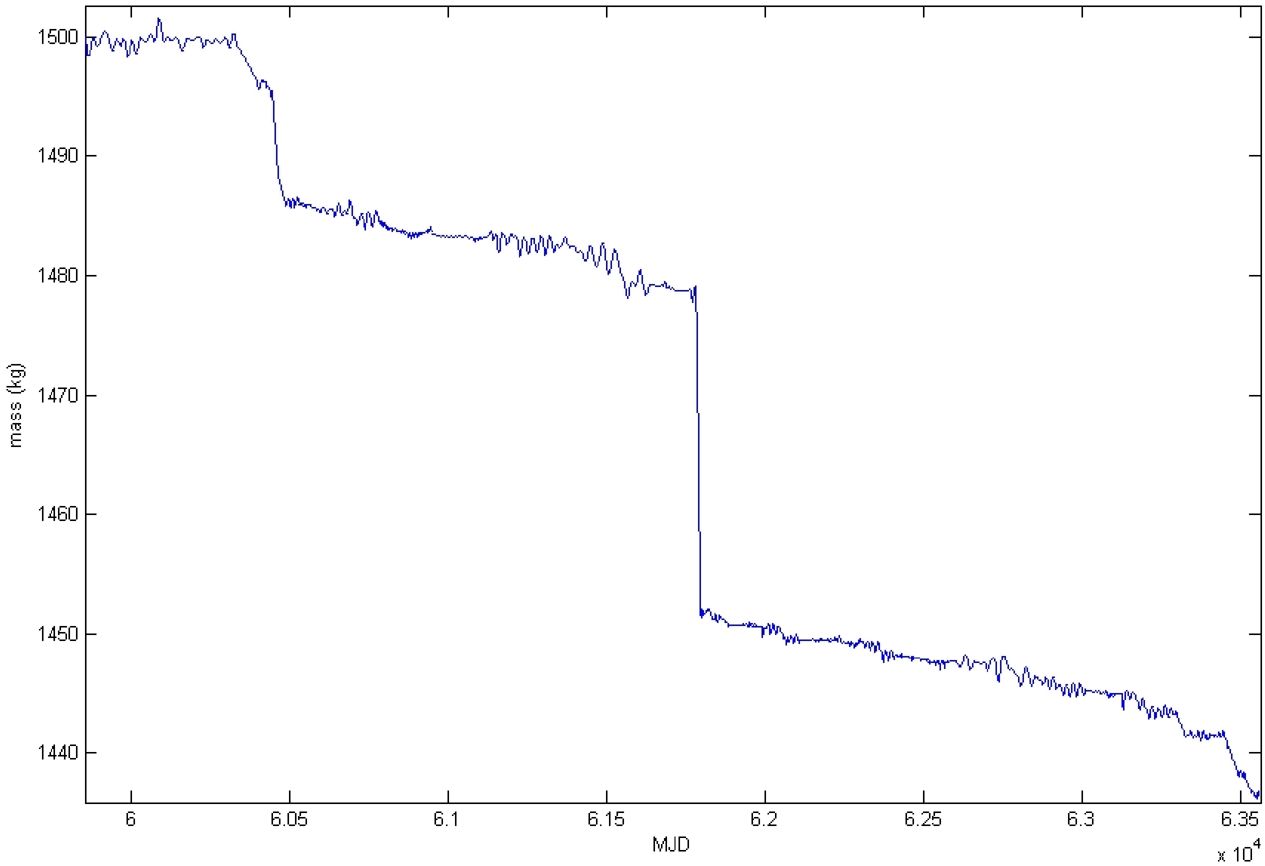

Figure 4: Mass variation over time.

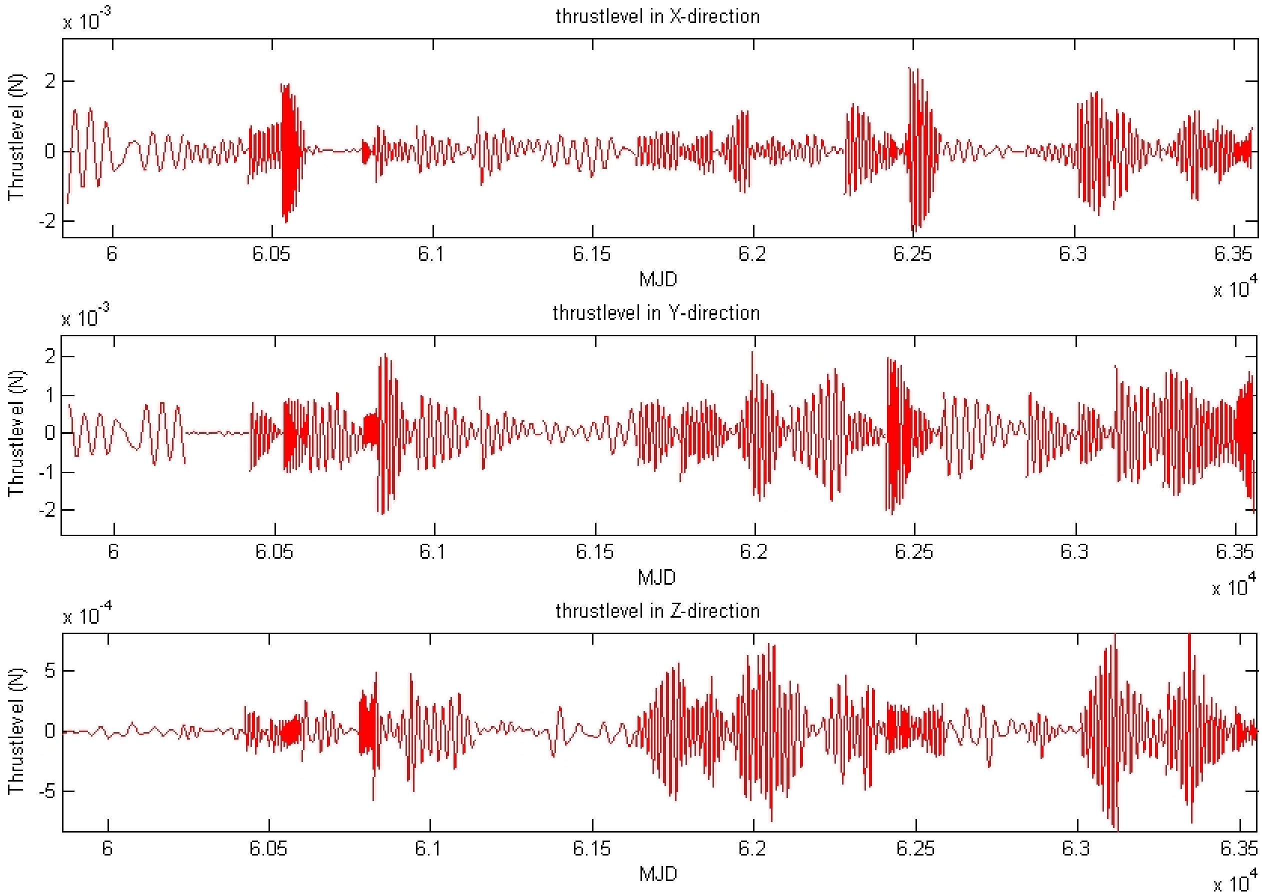

Figure 5: Thrust profiles in all three directions for the mission duration.

Table 1: All asteroids flown by.

Asteroid (GTOC4 name)	**Encounter date** (MJD)	**Mass at encounter** (kg)
153792	60222.6996	1499.7003
1997UH9	60423.5746	1496.2676
2007AH12	60527.7117	1486.1553
2001HY7	60601.4404	1485.5043
2006SD25	60778.8617	1484.8796
1999TT16	60820.8894	1483.9586
2005ML13	60946.8478	1483.6546
2002XY39	61139.3061	1483.2905
2008EV68	61339.7228	1482.6291
136923	61633.8552	1479.3222
10165	61766.0736	1478.7799
2006SV5	61874.7853	1450.9923
2007US65	61988.417	1450.5339
2005YN128	62109.7407	1449.6091
2005GW119	62284.6705	1449.3002
2005VY1	62408.4205	1448.2988
2002DQ3	62486.8957	1448.0071
2004TP1	62586.5194	1447.6719
1998HM3	62847.4300	1446.4612
2002EM7	63008.1673	1445.374
2004LK	63124.0819	1444.9938
2007YF	63274.1861	1443.4473
2005MO13	63392.4831	1441.5118
2004SB56	63495.0364	1438.3883
2008UA202	63553.8568	1436.4247

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