Preliminary mission design for Main-belt Asteroids multi-flybys exploration

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Abstract
As one of the preliminary mission design for Post-MUSES-C (HAYABUSA) Mission, Main-belt Asteroids multi-flybys exploration is studied. As the first step, this paper performs a selection of flyby exploration targets using ballistic orbit, and using these results, the multiple flybys trajectory to Main-belt asteroids by impulsive thrust or continuous low thrust is designed.

1. Introduction
The MUSES-C (HAYABUSA) which is the world’s first sample return mission spacecraft was successful launched toward a near earth asteroid 1998SF36 (ITOKAWA) on May 9th, 2003.
Presently, as one of the preliminary mission design for Post-MUSES-C (HAYABUSA) mission, main-belt asteroids multi-flybys exploration is proposed. In this paper, we explored the possibility of main-belt asteroids multi-flybys exploration mission.

There are more than tens of thousands of asteroids whose orbits are known, between the orbits of Mars and Jupiter (Figure1). And this number is increasing day by day by the observation[9]. These asteroids are categorized by shape, size, composition and mass. And there are various spectral types of asteroids. In addition, since asteroid’s size is very small, data which one asteroid has is very limited. For this reason, multiple flybys exploration is very useful for asteroid exploration.

There are crucial differences between one planet exploration and multiple asteroids exploration. Unlike in the case of planet exploration, asteroids exploration has so many targets candidates to be explored that there must be some sort of selection criteria to determine the best targets combination. And a mission sequence of asteroids exploration using multiple flybys depends largely on exploration targets. For this reason, the stage of choosing the candidates of exploration is important.

In this study, first, the targets combination search strategy which uses a ballistic orbit is proposed, and using these results, the multiple flybys trajectory to Main-belt asteroids by impulsive thrusts or low and continuous thrust is designed.

Figure1. Main-belt Asteroid
In this paper, mission target asteroids are selected, as follows,

1. Binary near Earth Asteroid (NEA)
   An asteroid that consists of two roughly equal parts that revolves around each other at close range. In this paper, we deal with Binary near Earth Asteroid in Ref. [6].

2. Asteroid Family
   Members of Main-belt asteroid family have nearly identical orbital elements\(^{(9)}\). In this paper, Koronis Family and Nysa Family are selected due to its large number of membership and the most accessible location for spacecraft.

2. Strategy
   In this paper, we constructed two multiple sequence search strategy, as follows,

   Case1: Priority asteroid mission design
   1. Select one of high priority targets from all the main-belt asteroids.
   2. Use Lambert’s law to search trajectory which passes through selected asteroid (Primary).
   3. Pick up one asteroid, seek the minimum distance between the asteroid and the trajectory and evaluate if it is within flyby threshold distance.

   Case2: Asteroid Group mission design
   1. Select priority group to explore.
   2. Find the results of the number of accessible asteroids in selected group per trajectory on the basis of flyby threshold distance.
   3. Pick out trajectories which can access the maximum number of asteroids and evaluate above results by relative distance.

These strategies are applied to the selected mission targets, as follows,
1. Binary NEA □ Case1&Case2
2. Asteroid Family □ Case2

3. Evaluation of delta-V
   We evaluate necessary delta-V to pass through (relative distance = 0km) the exploration target asteroid which was selected by strategy Case2. The total delta-V is evaluated both by impulsive thrust and low-thrust as follows,

   1. The transfer adjusted by impulsive thruster.
   We apply Lambert's law to passes between two asteroids. By varying each flyby time, total delta-V is optimized.
2. The transfers adjusted by low-thrust propulsion system. The steering law is optimized as minimum fuel consumption problem by DCNLPC (Direct Collocation with Nonlinear Programming) [2].

4. Mission Design 1 (Binary NEA)

5-1 Binary NEA: Case 1

Mission Assumed
2. Departure time □ 2013/01/01~2016/01/01
3. Absolute magnitude of target asteroid < 20M
4. Flyby Threshold < 3 \( \times 10^6 \)km

Results
Flyby sequences which pass through more than one binary asteroid are shown in Table 1. And the minimum total delta-V trajectory is shown in Figure 4, 5 and summary of the trajectory is shown in Table 2.

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### Table 1. Application of Flyby sequence search strategy

<table>
<thead>
<tr>
<th>Binary Asteroid</th>
<th>Departure time (EDVEGA)</th>
<th>Vinf</th>
<th>relative velocity</th>
<th>Extra flyby opportunity</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) 1994 AW1(H=17.05)</td>
<td>2014/12/13</td>
<td>0.18285km/s</td>
<td>12.358km/s</td>
<td>1</td>
</tr>
<tr>
<td>(2) Dionysus(H=16.3)</td>
<td>2015/07/13</td>
<td>3.6981km/s</td>
<td>8.9534km/s</td>
<td>1</td>
</tr>
<tr>
<td>(3) 1992 AX(H=13.9)</td>
<td>2013/07/11</td>
<td>4.3296km/s</td>
<td>6.5888km/s</td>
<td>5</td>
</tr>
<tr>
<td>(4) 1999 HF1(H=14.4)</td>
<td>2013/07/16</td>
<td>2.4440km/s</td>
<td>19.732km/s</td>
<td>1</td>
</tr>
<tr>
<td>(5) 1998 ST27(H=19.50)</td>
<td>2014/12/21</td>
<td>0.97929km/s</td>
<td>15.692km/s</td>
<td>1</td>
</tr>
<tr>
<td>(6) 2001 SL9(H=17.42)</td>
<td>2014/04/05</td>
<td>1.8460km/s</td>
<td>9.5939km/s</td>
<td>1</td>
</tr>
<tr>
<td>(7) 1999DJ4(H=18.47)</td>
<td>2013/05/25</td>
<td>1.6753km/s</td>
<td>8.5732km/s</td>
<td>1</td>
</tr>
</tbody>
</table>

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### Figure 4. Spacecraft's Trajectory

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### Figure 5. Spacecraft’s Trajectory in Sun-Earth System

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### Table 2. Summary of Flyby Trajectory

<table>
<thead>
<tr>
<th>Asteroid (Taxonomy)</th>
<th>H(Absolute Magnitude)</th>
<th>Flyby time from Earth Swing-by [day]</th>
<th>Relative distance [( \times 10^8 )km]</th>
<th>Relative velocity [km/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004 BL86</td>
<td>18.87</td>
<td>45</td>
<td>112.52</td>
<td>15.599</td>
</tr>
<tr>
<td>1994 AW1(Sa)</td>
<td>17.05</td>
<td>216</td>
<td>0.0</td>
<td>12.358</td>
</tr>
</tbody>
</table>

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5-2 Binary NEA: Case2

Mission Assumed
2. Departure time □ 2013/01/01~2016/01/01
3. Flyby Threshold < 3 \( \times 10^6 \)km

Results
Flyby sequences which pass through more than one binary asteroid are shown in Table 3. And three binary asteroids flyby trajectory is shown in Figure 6, 7 and summary of the trajectory is shown in Table 4.
Table 3. Flyby sequence

Two Binary Asteroids Flybys

<table>
<thead>
<tr>
<th>Primary</th>
<th>Secondary</th>
<th>Departure time (EDVEGA)</th>
<th>Vinf (Primary)</th>
<th>Relative velocity (Primary)</th>
<th>Extra flyby opportunity</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) 1998 PG (H:17.3)</td>
<td>1991 VH (H:16.9)</td>
<td>2015/04/14</td>
<td>V=4.3165km/s</td>
<td>9.6561km/s</td>
<td>1</td>
</tr>
<tr>
<td>(2) 1996 FG3 (H:18.38)</td>
<td>Hermes (H:17.5)</td>
<td>2015/06/22</td>
<td>V=3.7571km/s</td>
<td>6.1278km/s</td>
<td>0</td>
</tr>
<tr>
<td>(3) 2001 SL9 (H:17.42)</td>
<td>1992 AX (H:13.9)</td>
<td>2013/08/12</td>
<td>V=5.3794km/s</td>
<td>6.7699km/s</td>
<td>4</td>
</tr>
<tr>
<td>(4) 1990 HF1 (H:14.4)</td>
<td>1994 AW1 (H:17.05)</td>
<td>2013/07/30</td>
<td>V=5.1319km/s</td>
<td>15.05km/s</td>
<td>0</td>
</tr>
<tr>
<td>(5) 1999 KW4 (H:16.5)</td>
<td>2000 DP107 (H:18.05)</td>
<td>2015/10/17</td>
<td>V=3.1233km/s</td>
<td>19.120km/s</td>
<td>0</td>
</tr>
<tr>
<td>(6) 2001 SL9 (H:17.42)</td>
<td>1990 OS (H:19.31)</td>
<td>2013/08/06</td>
<td>V=5.7497km/s</td>
<td>12.918km/s</td>
<td>1</td>
</tr>
<tr>
<td>(7) Sekhmet (H:16.5)</td>
<td>1994 AW1 (H:17.05)</td>
<td>2014/07/20</td>
<td>V=4.1650km/s</td>
<td>22.376km/s</td>
<td>0</td>
</tr>
</tbody>
</table>

Three Binary Asteroids Flybys

<table>
<thead>
<tr>
<th>Primary</th>
<th>Secondary &amp; Tertiary</th>
<th>Departure time (EDVEGA)</th>
<th>Vinf (Primary)</th>
<th>Relative velocity (Primary)</th>
<th>Extra flyby opportunity</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) 1992 AX (H:13.9)</td>
<td>2003 SS84 (H:21.8)</td>
<td>2013/07/15</td>
<td>V=7.2471km/s</td>
<td>15.006km/s</td>
<td>8</td>
</tr>
<tr>
<td>2001 SL9 (H:17.42)</td>
<td>2003 SS84 (H:21.8)</td>
<td>2013/07/15</td>
<td>V=7.2471km/s</td>
<td>15.006km/s</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 4. Summary of Flyby Trajectory

<table>
<thead>
<tr>
<th>Asteroid (Taxonomy)</th>
<th>H (Absolute Magnitude)</th>
<th>Flyby time from Earth Swing-by (day)</th>
<th>V [m/s] (Impulsive)</th>
<th>V [m/s] (Low-Thrust)</th>
<th>Relative velocity [km/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001 SL9 (Sr)</td>
<td>17.42</td>
<td>94.3</td>
<td>4.2686</td>
<td>160.5883</td>
<td>15.032</td>
</tr>
<tr>
<td>1992 AX (S)</td>
<td>13.9</td>
<td>336.4</td>
<td>9.263</td>
<td>160.5883</td>
<td>7.2573</td>
</tr>
<tr>
<td>2003 SS84</td>
<td>21.8</td>
<td>494.3</td>
<td>4.925</td>
<td>160.5883</td>
<td>21.76</td>
</tr>
</tbody>
</table>

5. Mission Design 2 (Asteroid Family)

6-1 Nysa Family: Case 2

Nysa Family is applied to Strategy Case 2.

Mission Assumed

1. Application of EDVEGA\(^3\) \(\square\) Departure Vinf < ~6km/s
2. Departure time \(\square\) 2013/01/01~2016/01/01

3. Flyby Threshold < 3 \(\square\) 10\(^6\)km

Results

8 types Flyby sequences are obtained. Among those solutions trajectory with the minimum total relative distance is shown in Figure 8, 9 and the summary of the trajectory is shown in Table 6.
Table 6. Summary of Flyby Trajectory

<table>
<thead>
<tr>
<th>Asteroid (Taxonomy)</th>
<th>H (Absolute Magnitude)</th>
<th>Flyby time from Earth Swing-by (Day)</th>
<th>$\Delta V$ [m/s] (Impulsive)</th>
<th>$\Delta V$ [m/s] (Low-Thrust)</th>
<th>Relative velocity [km/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000 CE33</td>
<td>16.2</td>
<td>210</td>
<td>470.43</td>
<td>7.5037</td>
<td>2011</td>
</tr>
<tr>
<td>1998 RX64</td>
<td>15.3</td>
<td>232</td>
<td>386.01</td>
<td>7.1632</td>
<td></td>
</tr>
<tr>
<td>Beltrami</td>
<td>14.8</td>
<td>284.2</td>
<td>76.812</td>
<td>7.8816</td>
<td></td>
</tr>
<tr>
<td>Nysa(E)</td>
<td>7.03</td>
<td>508.9</td>
<td>8.0996</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) Departure time (EDVEGA) 2013/08/02 Vinf 5.8687 km/s

(2) Departure time (EDVEGA) 2013/07/11 Vinf 5.8974 km/s

(3) Departure time (EDVEGA) 2013/08/03 Vinf 5.8967 km/s

(4) Departure time (EDVEGA) 2013/07/04 Vinf 5.7892 km/s

(5) Departure time (EDVEGA) 2013/06/21 Vinf 5.7477 km/s

(6) Departure time (EDVEGA) 2013/07/29 Vinf 5.9680 km/s

(7) Departure time (EDVEGA) 2013/07/15 Vinf 5.7497 km/s

(8) Departure time (EDVEGA) 2013/07/27 Vinf 5.8281 km/s

Table 5. Flyby sequence (Nysa Family)

Figure 8. Spacecraft's Trajectory

Figure 9. Spacecraft's Trajectory in Sun-Earth System
6-2 Koronis Family: Case2
Koronis Family is applied to Strategy Case2.

Mission Assumed
1. Application of EDVEGA\(^{(3)}\) Departure Vinf < ~6km/s
2. Departure time  □  2013/01/01~2016/01/01
3. Flyby Threshold < 3 ⋅ 10^6 km

4. Taking advantage of Mars swing-by

Results
Flyby sequences which pass through three Koronis family asteroids are obtained. This trajectory is shown in Figure 10, 11 and the summary of this trajectory is shown in Table 7.

![Figure 10. Spacecraft’s Trajectory](image1)

![Figure 11. Spacecraft’s Trajectory in Sun-Earth System](image2)

<table>
<thead>
<tr>
<th>Event</th>
<th>Elapsed time from Earth Swing-by [day]</th>
<th>Periapse [km]</th>
<th>Relative velocity [km/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mars Swingby</td>
<td>103.0</td>
<td>7561</td>
<td>12.856</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Asteroid (Taxonomy)</th>
<th>H(Absolute Magnitude)</th>
<th>Flyby time from Earth Swing-by [day]</th>
<th>□ V [m/s] (Impulsive)</th>
<th>□ V [m/s] (Low-Thrust)</th>
<th>Relative velocity [km/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000 WS94</td>
<td>14.6</td>
<td>360.7</td>
<td>280.65</td>
<td>1487.5</td>
<td>6.4434</td>
</tr>
<tr>
<td>Leucorodia</td>
<td>13</td>
<td>475.7</td>
<td>695.86</td>
<td></td>
<td>5.0093</td>
</tr>
<tr>
<td>Ida(S)</td>
<td>9.94</td>
<td>550.4</td>
<td></td>
<td></td>
<td>5.25</td>
</tr>
</tbody>
</table>

6. Conclusion
We investigated multiple asteroid flybys opportunities and demonstrated that there are several feasible mission plans using chemical propulsion or low-thrust propulsion to conduct flybys. For these results, we insist three and four asteroids flybys in a single flight is feasible.

7. References


[5] Lowell observatory, astorb.dat