Available online at www.sciencedirect.com
SCIENCE DIRECT®
Advances in Space Research 34 (2004) 2281–2285
ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
www.elsevier.com/locate/asr

# Trajectory design of multiple asteroid sample return missions

M. Morimoto [a,*], H. Yamakawa [b], M. Yoshikawa [b], M. Abe [b], H. Yano [b]

[a] The Graduate University for Advanced Studies, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan
[b] Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan

Received 19 October 2002; received in revised form 16 October 2003; accepted 20 October 2003

## Abstract

As one of the potential candidates of the "post-MUSES-C" minor body exploration to be launched around 2010, we have investigated scientific justifications and feasible mission scenarios. Two mission types are focused on among many other proposed mission concepts. One is the multiple rendezvous and sample return mission to asteroids whose spectral type is already known. The other is the multiple fly-bys and sample return mission to an asteroid family. This paper reports the preliminary design results of these two proposed missions.

*Keywords:* Multiple asteroid sample return missions; Multiple rendezvous; Asteroid research; Proposed missions

## 1. Introduction

ISAS MUSES-C is the world's first asteroid sample return mission. Its launch is scheduled in the spring of 2003. It is defined as an engineering validation mission for major new technologies necessary for future planetary sample return missions. Following up the MUSES-C, the next generation of Japanese minor body explorations has been discussed for last 2 years (Yano and Kawaguchi, 2002), and two promising candidates have been identified. One of them is a multiple asteroid sample return mission aiming at several spectral known near earth asteroids. Its objective is to link major asteroid taxonomy with meteorite and cosmic dust samples. The other is also a multiple asteroid sample return mission, but from main belt asteroid family members (e.g., Koronis), which may provide direct information to reconstruct the interior of their parent planetesimal and its impact disruption history.

In this paper we investigate the preliminary designs of technically feasible trajectories for both of these mission candidates. In addition, in order to meet the above two scientific objectives in one mission, trajectories for sample returns from the family that holds several spectral types within (i.e., Nysa-Polana) are also studied. H2-A class launch vehicles and chemical or electric propulsions are assumed.

## 2. Mission design

### 2.1. Multiple spectrally known asteroids rendezvous and sample return mission

As multiple rendezvous and sample return from spectrally known asteroids, we selected near earth objects (NEO) from a deliverable payload mass point of view. Table 1 shows the candidates of such NEO targets. Three sequences are considered and the examples below assume two asteroids:

1. Single rocket, one spacecraft, multiple asteroids and no Earth swing-by: Earth → Asteroid 1 → Asteroid 2 → Earth.
2. Single rocket, one spacecraft, multiple asteroids and Earth swing-by: Earth → Asteroid 1 → Earth swing-by (N-times) → Asteroid 2 → Earth.
3. Single rocket, two spacecraft, multiple asteroids: Earth → Earth swing-by → A. Asteroid 1/B. Asteroid 2 → Earth.

---

[*] Corresponding author. Tel.: +81-42-759-8508; fax: +81-42-759-8243.
*E-mail address:* mutsuko@pub.isas.jaxa.jp (M. Morimoto).

0273-1177/$30 © 2004 COSPAR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.asr.2003.10.055

Table 1
The candidates of mission target NEOs

| | |
|---|---|
| C type | Nereus, Anza, Wilson-Harrington, Hathor |
| S type | Anteros, 1982XB, Bivoj, 1991VK, Eros, Seleucus, Ivar, Toutatis |
| V type | Orpheus, Nyx, Verenia |
| Q type | 1992LR, 1993VW, 1980WF |
| M type | 1986DA |
| E type | 1989ML |
| D type | Beronia |

Both sequences (1) and (2) show that one spacecraft is launched with one rocket. In sequence (1), the spacecraft goes to the next asteroid right after the first asteroid rendezvous. In sequence (2), the spacecraft brings the sample back to the earth every time the sample collection is made at one asteroid. Therefore, scientists are possible to analyze the first sample of asteroid earlier than sequence (1), although the total mission period is longer compared to sequence (1). Sequence (3) shows that two spacecrafts are launched with one rocket, and each spacecraft flies ahead to different target NEO asteroids after the Earth swing-by. In every sequences (1), (2) and (3), samples are returned to the earth.

Table 2 shows some examples of the sequences (1), (2) and (3) (Morimoto et al., 2000). In sequences (1) and (2), chemical propulsion is not allowed because a lot of fuel are used for rendezvous, thus electric propulsion is assumed. And the magnitude of $\Delta V$ is assumed approximately twice that of chemical propulsion $\Delta V$. In sequence (3), conventional chemical propulsion is assumed.

Spacecraft design for the multiple spectrally known asteroids rendezvous and sample return mission is summarized in Table 3. As for the launch vehicle, NASDA's H-2A (10 ton LEO capability) is assumed. For example, in sequence (2), the total mass of the spacecraft is 2243 kg. When the initial mass margin for spacecraft design is assumed as 5% of the total wet mass, the scientific payloads can be allowed up to 203 kg mass including sampling devices and return capsules.

### 2.2. Multi-Koronis family asteroid fly-by and sample return mission

For the main belt asteroid family mission, the Koronis family (156 main belt asteroids are currently identified) is considered as a reference target since it is not only the most accessible among the three major families in terms of the launch capability but also is of significant scientific interest (Yano et al., 2000).

The spacecraft makes multiple fly-bys with the Koronis asteroids during one revolution (second revolution for option) around the Sun and returns to the Earth for bringing samples back. To conduct sampling without rendezvous, 10 kg-order projectiles are released for oblique impacts on asteroids prior to the fly-by. Ejected materials from sub-surface in several meter depths will impact into low dense capture media (e.g., aerogels) at an encountering velocity of several km/s during the closest approach. The sample will be returned to Earth via direct capsule re-entry from interplanetary hyperbolic trajectory. There are several possible options for this mission including Earth, Venus and Mars gravity assists. However, this paper mainly focuses on the simplest sequence with no planetary swing-by with the emphasis on short mission duration.

Table 4 shows an example of an optimized asteroid fly-by sequence with six Koronis asteroids in 6-year flight time, whose trajectory plots are shown in Figs. 1 and 2 (Yamakawa et al., 2000). Trajectory correction maneuvers are assumed just after the asteroid fly-by points. The relative velocities before and after fly-by are also shown in Table 4. Rel. vel. 1 is the velocities before fly-by and rel. vel. 2 is the velocities after fly-by.

Spacecraft design for this case is summarized in Table 5. The total mass of the spacecraft is 1080 kg. When initial mass margin for spacecraft design is assumed as 5% of the total wet mass, the scientific payloads can be allowed up to 237 kg mass including sampling devices such as projectors, sample collectors and Earth return capsules.

Table 2
Example of multiple asteroids rendezvous and sample return mission

| No. | | Asteroids (type) | Propulsion/Earth SB | Launch day | Rendezvous periods | Earth return | Total mission duration |
|---|---|---|---|---|---|---|---|
| 1. | 1 spacecraft<br>2 asteroids | Nereus (C)<br>Bivoj (S) | Electric/No-earth SB | 2011.01.21 | 2013.04.03–2016.08.08/<br>2017.09.12–2017.10.12/ | 2019.01.20 | 8 years |
| 2. | 1 spacecraft<br>3 asteroids | 1989ML (E)<br>Orpheus (V)<br>Nereus (C) | Electric/Earth SB × 4 | 2012.07.09 | 2013.03.06–2014.04.10/<br>2018.01.04–2018.07.18/<br>2023.07.02–2023.09.20/ | 2016.06.18<br>2021.02.02<br>2026.01.27 | 14 years |
| 3. | 2 spacecraft<br>2 asteroids | Orpheus (V)<br>Nereus (C) | Chemical/Earth SB × 1 | 2014.01.05<br>2014.01.05 | 2017.08.02–2018.01.04/<br>2016.09.16–2017.01.09/ | 2021.04.08<br>2020.02.23 | 8 years<br>7 years |

SB, Swing-By.

Table 3
Multiple NEO asteroid mission spacecraft mass budget

| | (1) 1 S/C 2 asteroids | (2) 1 S/C 3 asteroids | (3) 2 S/C 2 asteroids |
|---|---|---|---|
| Wet mass | 1687 kg | 2243 kg | 1015/1017 kg (Orpheus/Nereus) |
| $C3$ | 23.3 $\text{km}^2/\text{s}^2$ | 8.65 $\text{km}^2/\text{s}^2$ | 13.8/13.7 $\text{km}^2/\text{s}^2$ |
| Nominal $\Delta V$ | 7650 m/s, $I_{\text{sp}} = 3000$ s | 22390 m/s, $I_{\text{sp}} = 3000$ s | 2727/2580 m/s, $I_{\text{sp}} = 320$ s |
| Navigation | 400 m/s, $I_{\text{sp}} = 3000$ s | 800 m/s, $I_{\text{sp}} = 3000$ s | 200/200 m/s, $I_{\text{sp}} = 320$ s |
| Total fuel | 404 kg | 1224 kg | 616/598 kg |
| Electric propulsion system | 100 kg | 100 kg | |
| Chemical propulsion | 100 kg | 100 kg | 77/78 kg[a] |
| Structure | 169 kg[b] | 224 kg[b] | 102/102 kg[b] |
| Power | 130 kg | 130 kg | 43/57 kg[c] |
| Bus | 150 kg | 150 kg | 117 kg[d] |
| Spacecraft Bus | 649 kg | 704 kg | 339/354 kg |
| Sampling mechanism | 15 kg | 15 kg | 15 kg |
| Earth return capsule | 40 kg | 120 kg (40 kg×3) | 40 kg |
| Science (on-board) | 494 kg | 68 kg | 28/10 kg |
| Total scientific instruments | 549 kg | 203 kg | 83/65 kg |
| Margin | 85 kg (5%) | 112 kg (5%) | – |

[a] Propulsion system ($0.6 * \text{fuel}(^{2/3}) + 35$ kg).

[b] Structure (wet mass × 0.10).

[c] Power (incl. paddle 80 kg 200 W@3.0 AU).

[d] Bus (communication 30 kg, Attitude and Orbit Control System (AOCS) 15 kg, Data Handling Unit (DHU) 10 kg, Timer 2 kg, Cables 30 kg, Thermal 30 kg).

Table 4
An example of four Koronis family asteroid fly-bys and sample return sequence in 6 years

| No. | Name | Epoch | Elapse day | $\Delta Y$ (m/s) | Rel. vel. 1 (km/s) | Rel. vel. 2 (km/s) |
|---|---|---|---|---|---|---|
| 1. | Earth | 2013.02.01 | 0 | Launch | Launch | Launch |
| 2. | 243Ida & Dactyl | 2014.02.28 | 392 | 224.59 | 6.5 | 6.5 |
| 3. | 2700 Baikonur | 2015.01.06 | 704 | 195.54 | 6.0 | 6.0 |
| 4. | Earth | 2016.01.28 | 1090 | 1st return | 7.0 | Extended |
| 5. | 1079 Mimosa | 2017.02.14 | 1472 | 132.38 | 6.9 | 6.9 |
| 6. | 933 Moultona | 2018.02.12 | 1835 | 178.53 | 6.9 | 6.9 |
| 7. | Earth | 2019.01.29 | 2168 | 2st return | 7.1 | Final body |

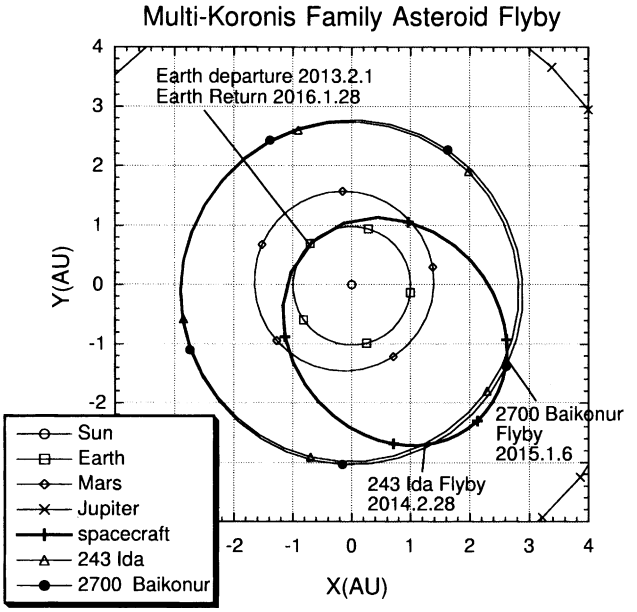

Fig. 1. The first revolution trajectory of the 4 Koronis family mission to visit Ida/Dactyl and Baikonur.

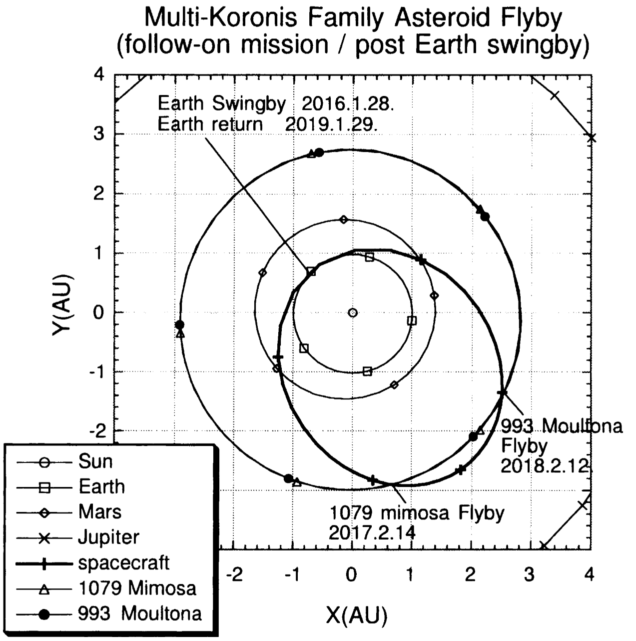

Fig. 2. The second revolution trajectory of the 4 Koronis family mission to Visit Mimosa and Moultona.

Table 5
Koronis & Nysa-Polana family mission spacecraft mass budget

| | Koronis family | Nysa-Polana family |
|---|---|---|
| | 4 asteroids in 6 years | 2 asteroids in 2 years |
| Wet mass | 1080 kg ($C3 = 47.2$ km$^2$/s$^2$) | 1213 kg ($C3 = 49.9$ km$^2$/s$^2$) |
| Injection error correction | 52 kg (150 m/s, $I_{sp} = 310$ s) | 57 kg (150 m/s, $I_{sp} = 320$ s) |
| Nominal $\Delta V$ at fly-bys | 220 kg (730 m/s, $I_{sp} = 310$ s) | 330 kg (1053 m/s, $I_{sp} = 320$ s) |
| Navigation | 46 kg (30 m/s × 6, $I_{sp} = 310$ s) | 24 kg (30 m/s × 3, $I_{sp} = 320$ s) |
| Attitude control | 25 kg (60 m/s, $I_{sp} = 180$ s) | 22 kg (50 m/s, $I_{sp} = 180$ s) |
| Total fuel | 358 kg (incl. capsule separation 15 g) | 433 kg |
| Propulsion system | 80 kg (0.6[a] fuel(2/3) + 50 kg) | 84 kg |
| Structure | 119 kg (wet mass × 0.11) | 121 kg (wet mass × 0.10) |
| Power | 100 kg (incl. paddle 80 kg; 200 W@3.0 AU) | 63 kg |
| Bus | 132 kg | 132 kg |
| Spacecraft Bus | 431kg | 400 kg |
| Projectile Shooting Mechanism | 120 kg (30 kg × 4) | 60 kg (30 kg × 2) |
| Sampling mechanism | 30 kg | 30 kg |
| Earth return capsule | 80 kg (40 × 2) | 40 kg |
| Science (on-board) | 7 kg | 189 kg |
| Total science instruments | 237 kg | 319 kg |
| Margin | 54 kg (5%) kg | 61 kg (5%) kg |

[a] Bus (Communication 30 kg, AOCS 15 kg, DHU 10 kg, Timer 2 kg, Cables 35 kg, Thermal 40 kg).

Table 6
An example of two Nysa-Polana family asteroid fly-bys and sample return sequence in 2 years

| No. | Name | Spectral type | Epoch | $V$ (m/s) | Rev. vel. 1 (km/s) | Rev. vel. 2 (km/s) |
|---|---|---|---|---|---|---|
| 1. | Earth | | 2011.02.01 | Launch | Launch | 39.96($C3$) |
| 2. | Hertha | M-type | 2011.09.27 | 615 | 9.87 | 9.82 |
| 3. | Hillary | F-type | 2011.11.13 | 438 | 9.12 | 8.98 |
| 4. | Earth | | 2013.01.31 | Final body | 37.42($C3$) | Final body |

### 2.3. Nysa-Polana family asteroid fly-bys and sample return misson

We also investigated options going to the Nysa-Polana family. It is not among the three major families but still holds more than 130 members at $a = 2.4$ AU with relatively low orbital plane inclinations. The unique characteristic of this family is that it contains several different spectral types. The largest members of the family include Nysa of the E-type, Hertha of the M-type and Polana of the F-type. Also the orbital parameters split this family to the Nysa and the Polana sub-groups, whose major spectral types are the S-type arid the F-type, respectively. Thus this family may be resultant of either a mutual collision between a differentiated planetesimal (M–E–S types from the core to the exterior?) and a less differentiated one in comparable sizes, or merging of two completely different break-ups. Should this mission be viable, it would benefit not only studies of impact history and the interior of the planetesimal but also those of asteroid taxonomy to collect samples from several different types in one flight (Yano et al., 2001).

Table 6 shows an example of an optimized asteroid fly-by sequence with two Nysa-Polana asteroids (M-type and F-type) in 2-year flight time, whose trajectory plot is shown Fig. 3. Trajectory correction manoeuvres are also assumed just after the asteroid fly-by points. The relative velocities before and after that fly-by are also shown in Table 6.

Spacecraft design of this case is summarized in Table 5. The total mass of the spacecraft is 1213 kg and the scientific payloads can be allowed up to 319 kg mass including sampling devices such as projectors, sample collectors arid an Earth return capsules.

## 3. Trajectory design method

In the trajectory design of the above missions, the conventional method is to divide the sequence into segments as Earth–asteroid leg, asteroid–asteroid leg, and asteroid–Earth leg and then to find a trajectory candidate satisfying many constraints (e.g., payload mass, different spectral types, etc.) by connecting each subsequence. However, it is difficult to find several candidates among a huge number of combinations of segment trajectories. Therefore, the Genetic Algorithm (GA method) is introduced as a trajectory design method for these multiple asteroids missions. This algorithm makes a group of solutions called “population”, and solution candidates of the group called

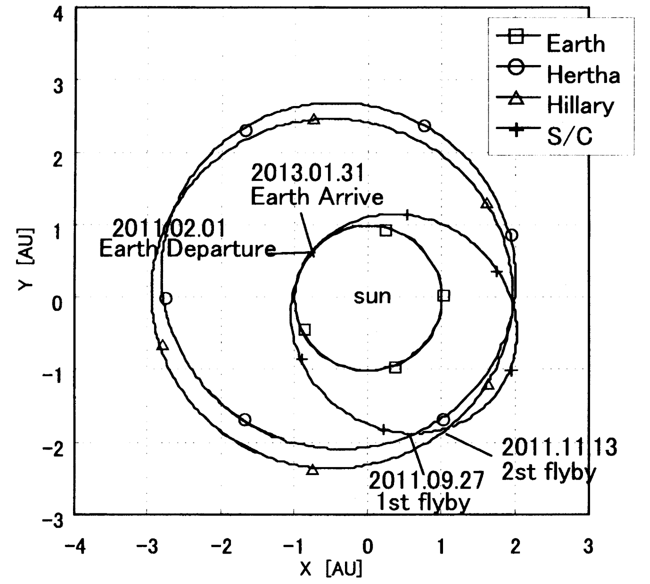

Fig. 3. Trajectory of the Nyda-Polana family mission to Hertha and Hillary.

- Control parameter

Asteroids(Asteroid1, Asteroid2)
Departure ･Arrival Date(flight time : t1, t2, t3, ････)

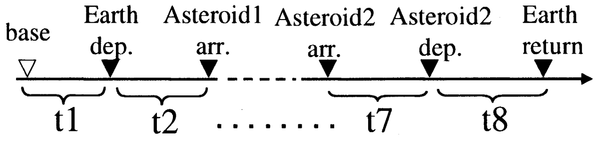

Fig. 4. GA method control parameter.

"gene" duplicate "cross-over" and "mutation" in order to make the next generations (Reeves, 1993). And then it converges to an optimum solution. Utilizing the GA method, we are able to search out trajectories candidates that brute search requires enormous calculation time.

The characteristics of the GA methods can be summarized as follows:

1. The gene called "Chromosome", which encodes the variable is used to search for the solution. Therefore, discrete variables can be treated.
2. It searches not from one point of the design area but from a lot of points simultaneously.
3. Only the performance index value is used for the evaluation of the solution, and the differential value of the performance index is not used.
4. This method is not deterministic but probabilistic.
5. The parameters of trajectory designs are target asteroids, dates of departure and arrival (Fig. 4).

## 4. Conclusion

Three types of asteroid sample return mission are proposed which are scientifically promising and technically feasible. Nysa-Polana family mission, the spacecraft brings the sample back to Earth from two asteroids of different spectral types in 2 years.

## References

Reeves, C.R. Using genetic algorithms with small populations, in: Forrest, S. (Ed.), Proc. of 5th International Conference on Genetic Algorithms. Morgan Kaufmann, San Mateo, CA. pp. 92–99, 1993.

Morimoto, M., Yoshida, S., Yamakawa, H., Yoshikawa, M., Abe, M., Yano, H., Fujiwara, A. In: Trajectoriy Design of Multiple Rendezvous and Sample, Return Mission to NEO Asteroids. Proc. of the 21st Solar System Science Symp., Sagamihara, Japan, ISAS, pp. 64–68, 2000 (in Japanese).

Yamakawa, H., Yoshikawa, M., Abe, M., Fujiwara, A., Yano, H. In: Exploration of an Asteroid Family: Flyby and Sample Return Mission to Multiple Mainbelt Asteroids. Proc. of the 22nd International Symposium on Space Technology and Science (ISTS), ISTS 2000-o-3-08v, Morioka, Japan, 2000.

Yano, H., Kawaguchi, J., Akiyama, H. Minorbody exploration forum, in: Case Studies of Next Generation Primitive Body Exploration Missions. Proc. of the 2nd Space Science Symp., Sagamihara, Japan, ISAS, pp. 335–342, 2002 (in Japanese).

Yano, H., Abe, M., Yamakawa, H., Yoshikawa, M., Fujiwara, A. In: The Family Mission: Multiple Fly-bys and Sample Returns to Main Belt Asteroid Families. Asteroids 2001, Abst., Sicily, Italy, 2001.

Yano, H., Yoshikawa, M., Abe, M., Fujiwara, A., Yamakawa, H., Katayama, M. In: A Mission to a Lost Planetesimal: Scientific Goals and Engineering Feasibility of Multiple Fly-bys and Sample Return Mission to an Asteroid Family. Proc. of the 21st Solar System Science Symp., Sagamihara, Japan, ISAS, pp. 68–71, 2000.