Sustainable Asteroid Mining

Results and methods of team BIT-CAS-DFH

Zhang Yining

Beijing Institute of Technology

Team Members







Zhu Zhengfan Zhang Yang Pang Bo Zhang Guoxu Sun Yangyuxi Zhu Tianhao

Wen Changxuan

Shang Yunong


Gao Yang

Zhang Yining

Beijing Institute of Technology

Center for Space Utilization, CAS

DFH Satellite CO., Ltd.

Aerospace Information Research Inst., CAS


Peng Chao

Jin Zihan







He Shengmao Yin Yongchen Zhou Rui Lu Meng He Lvzheng Li Zhaohang Wang Yangxin

Outline

1. Preliminary Analysis

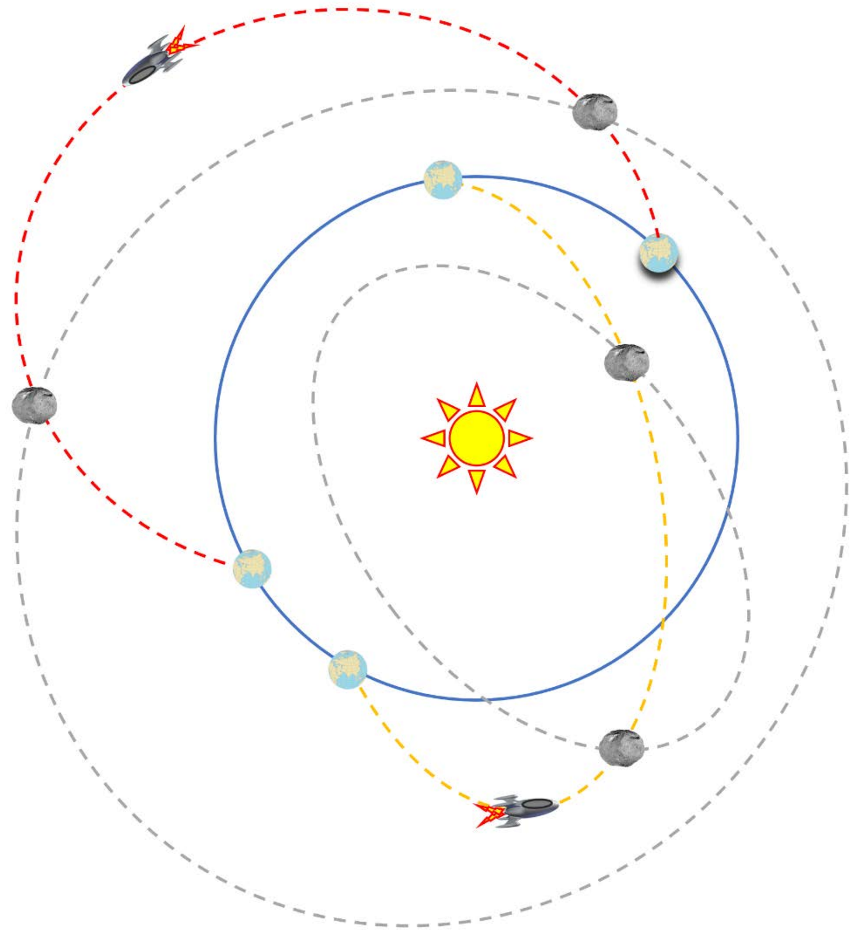
2. Method

2.1 Databases building

2.2 Asteroid visiting sequences searching

2.3 Low-thrust trajectory converting

3. Results and Discussion

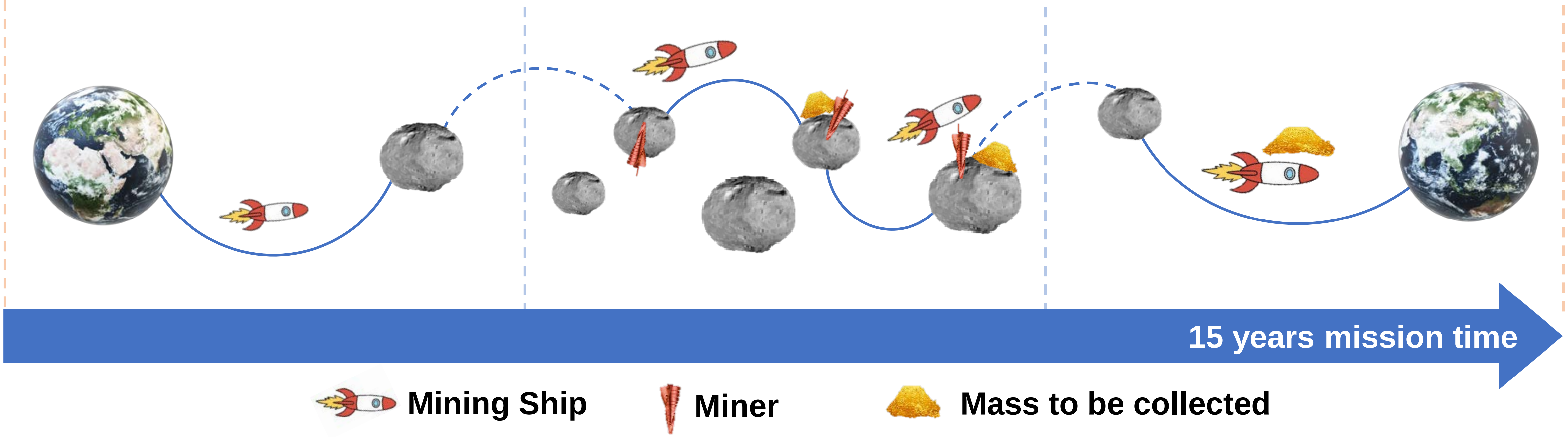


Preliminary Analysis

Mission Phases

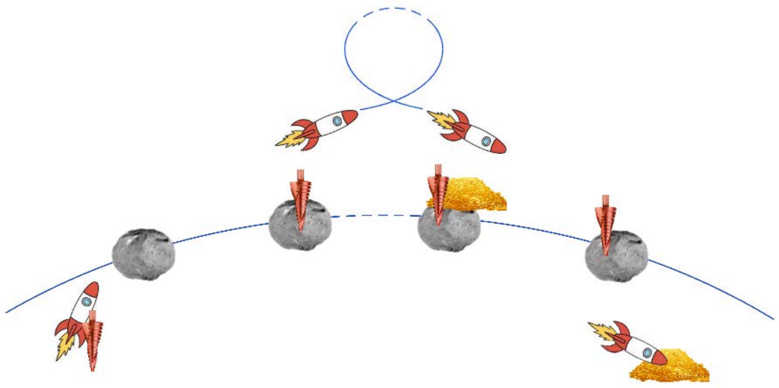
- ✓ Mining mission is divided into 3 phases
- ✓ Different kind of asteroid rendezvous strategies available for phase 2

Phase 1: Earth to Asteroid	Phase 2: Asteroid to Asteroid	Phase 3: Asteroid to Earth



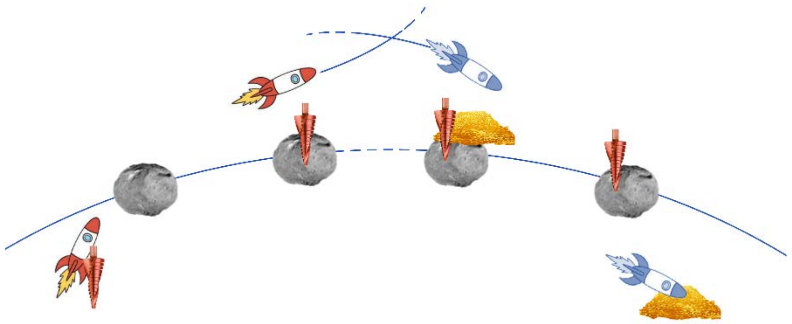
Mining Strategies for Phase 2

Strategy a



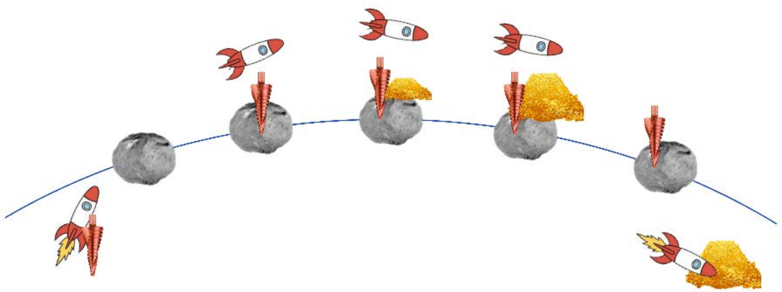
- ✓ No interference between Ships
- ✓ Easy for parallel design
- ✓ Easy for adding new ships
- × Lower theoretical upper bound

Strategy b



- ✓ Higher theoretical upper bound
- ✓ Larger space to search
- × Higher computing load
- × Sequence design bundled with other ship

Strategy c



- ✓ The most fuel saving scheme
- ✓ Can be used for patching
- × High time cost

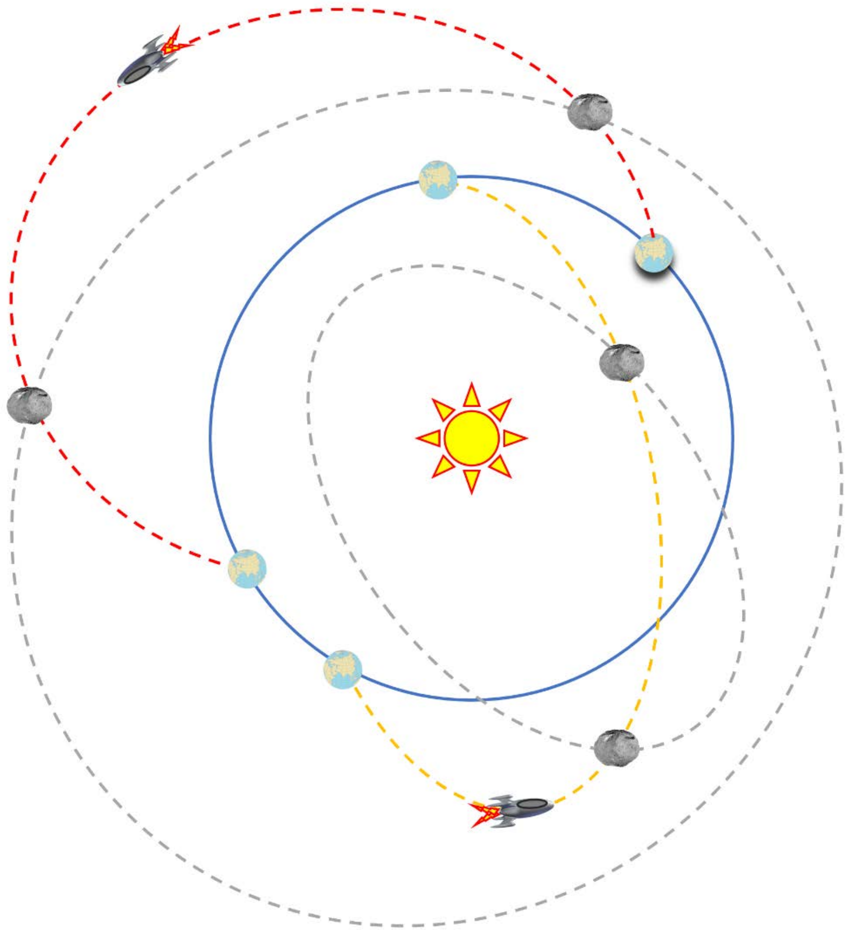
Outline

1. Preliminary Analysis

2. Method

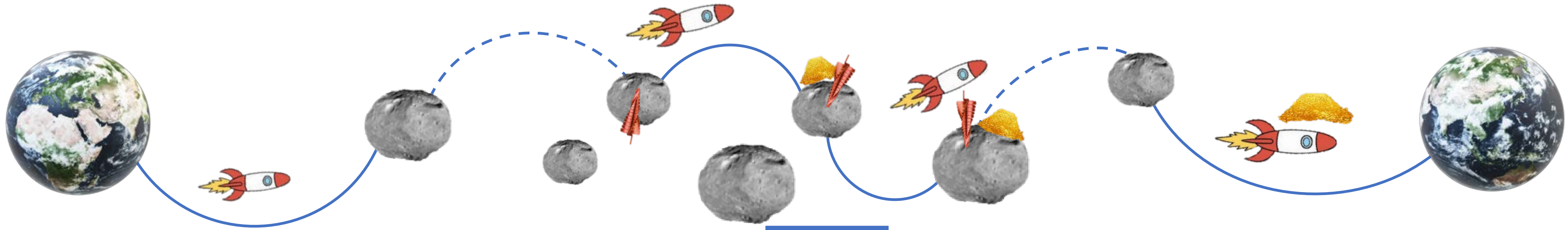
- 2.1 Databases building
- 2.2 Asteroid visiting sequences searching
- 2.3 Low-thrust trajectory converting

3. Results and Discussion

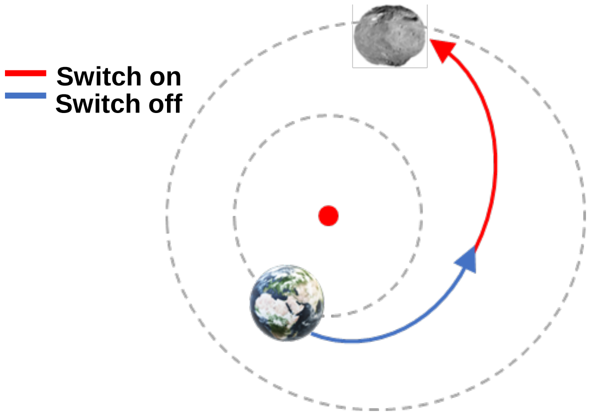


2 Method: Databases building

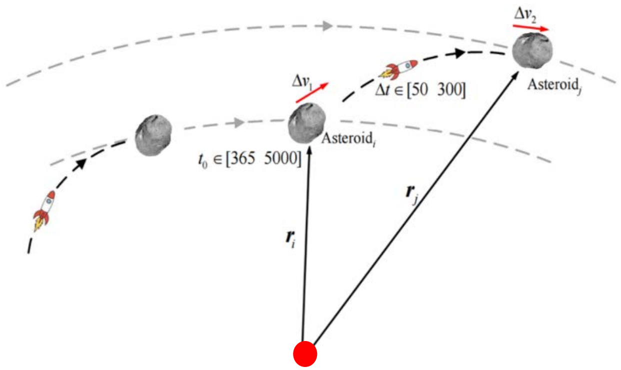
Phase 1: Earth to Asteroid	Phase 2: Asteroid to Asteroid	Phase 3: Asteroid to Earth



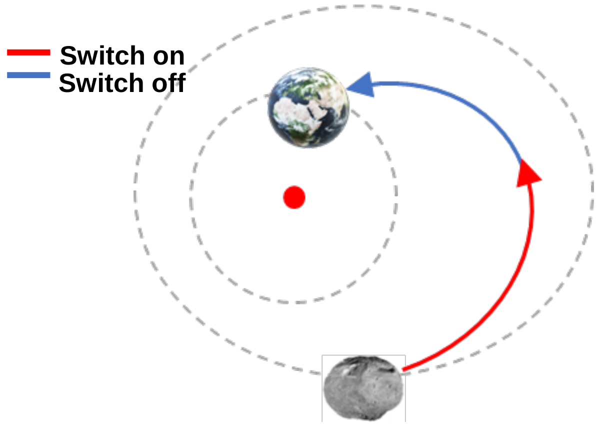
Database 1: Earth to Asteroid



Database 2: Asteroid to Asteroid



Database 3: Asteroid to Earth



Method: Databases building

Earth-Asteroid and Asteroid-Earth databases

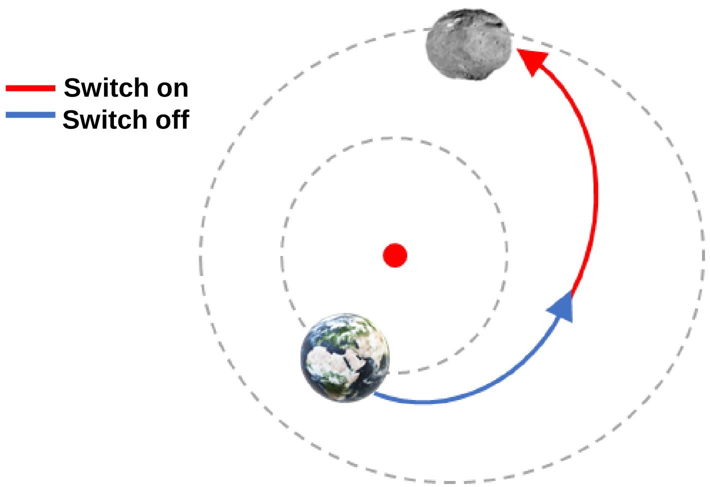
Step 1
Fuel efficient Lambert transfers

Step 2
Time optimal Low-thrust transfer

Step 3
Pruning for early arrival and late return

Earth to Asteroid

Transfer model: coast + thrust

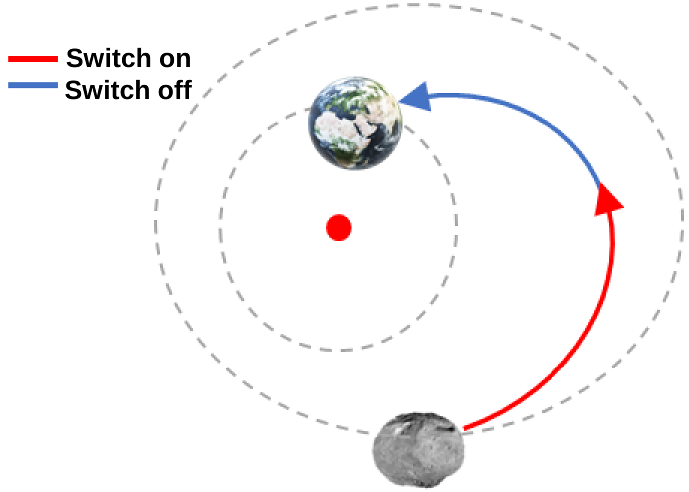


Arrival time from the mission start date	<1.5 year

Database 1: 18170 feasible asteroids

Asteroid to Earth

Transfer model: thrust + coast



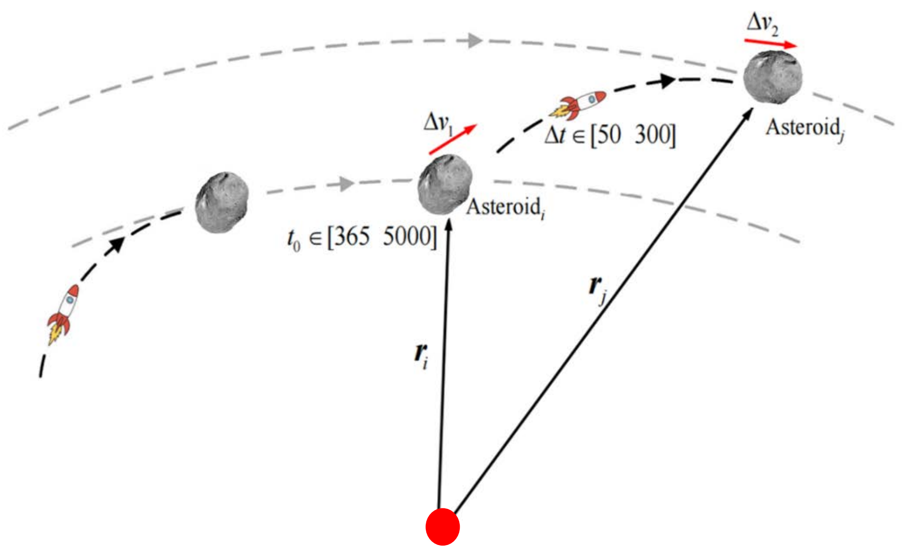
Departure time to the mission end date	<1.5 year

Database 3: 24319 feasible asteroids

Method: Databases building

□Asteroid-Asteroid database

- Lambert transfer is adopted
- C++ parallel computing platform
- NVIDIA TITAN RTX GPU



Search parameters	Range
Asteroid ID	1-60000
Departure epoch (days)	365-5000
Transfer time (days)	50-300

1.79997×10^9 asteroid-asteroid transfers

Pruning conditions: T<0.6 N; ΔV < 2 km/s

	ID_1	ID_2	ΔV	τ_0	τ_f
1	1	2	ΔV_{12}	τ_1	τ_2
2	1	3	ΔV_{13}	τ_3	τ_4
⋮	⋮	⋮	⋮	⋮	⋮
N					

- ✓ 1.5076249×10^8 survival results
- ✓ Database created in three days

Method: Asteroid visiting sequences

Mission segments

Straightforward two segments strategy

Segment 1 | Segment 2

Difficulty

- Very long sequences facing computational issues
- The number of sequences exceeds 10^{10}, when searching to the 8th node (~ 7 years).

Why not paying more attention on areas that can score higher?

Four segments strategy

Segment 1 | Segment 2 | Segment 3 | Segment 4

Time Forward

Time Backward

Secondary scoring segments

Priority scoring segments

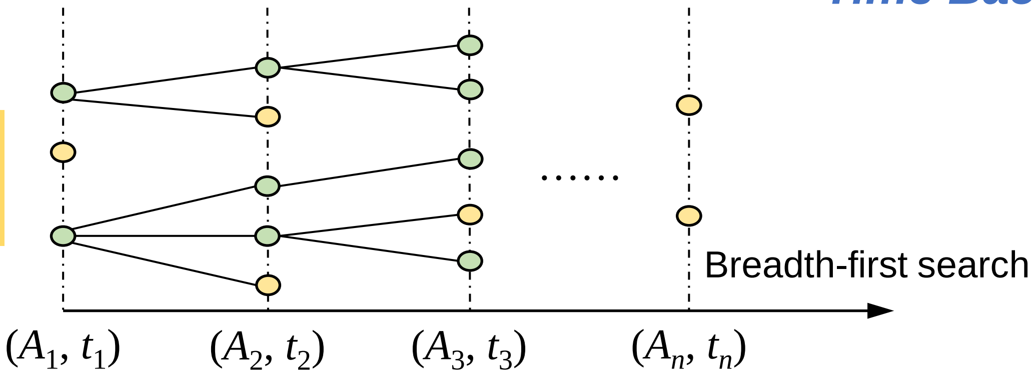
Method: Asteroid visiting sequences

Sequences for Segments 1 and 4

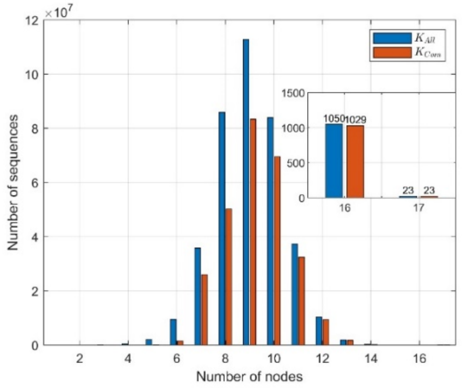
Segment 1 | Segment 2 | Segment 3 | **Segment 4**

Time Forward | *Time Backward*

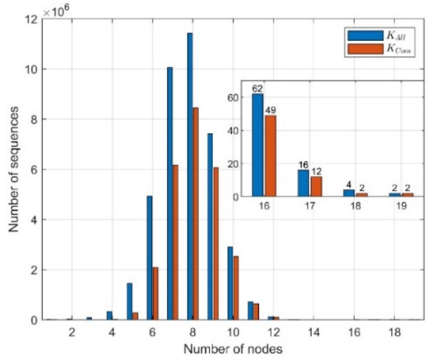
Beam Search (Breadth-first)



- **Number of sequences** **274,583,439**
- **Average length of sequences** **9.23**



- **Number of sequences** **26,392,705**
- **Average length of sequences** **8.08**



2 Method: Asteroid visiting sequences

Selection of sequence candidates for Segment 1 and Segment 4

Segment 1 | Segment 2 | Segment 3 | Segment 4

Time Forward | *Time Backward*

Step 1. Data pruning

1. Matching the asteroid with databases 1 and 4

Segment 1 — the first asteroid; Segment 4 — the last asteroid; compare

2. Sorting the sequences by the average visiting time
3. Sorting the sequences by the number of asteroid visited

Survival sequences in **Segment 1**: **90,427**
Survival sequences in **Segment 4**: **134,485**

Step 2. Searching for high-score combinations

GA

fitness function:
average mining mass of the selected and output sequences

The output sequences

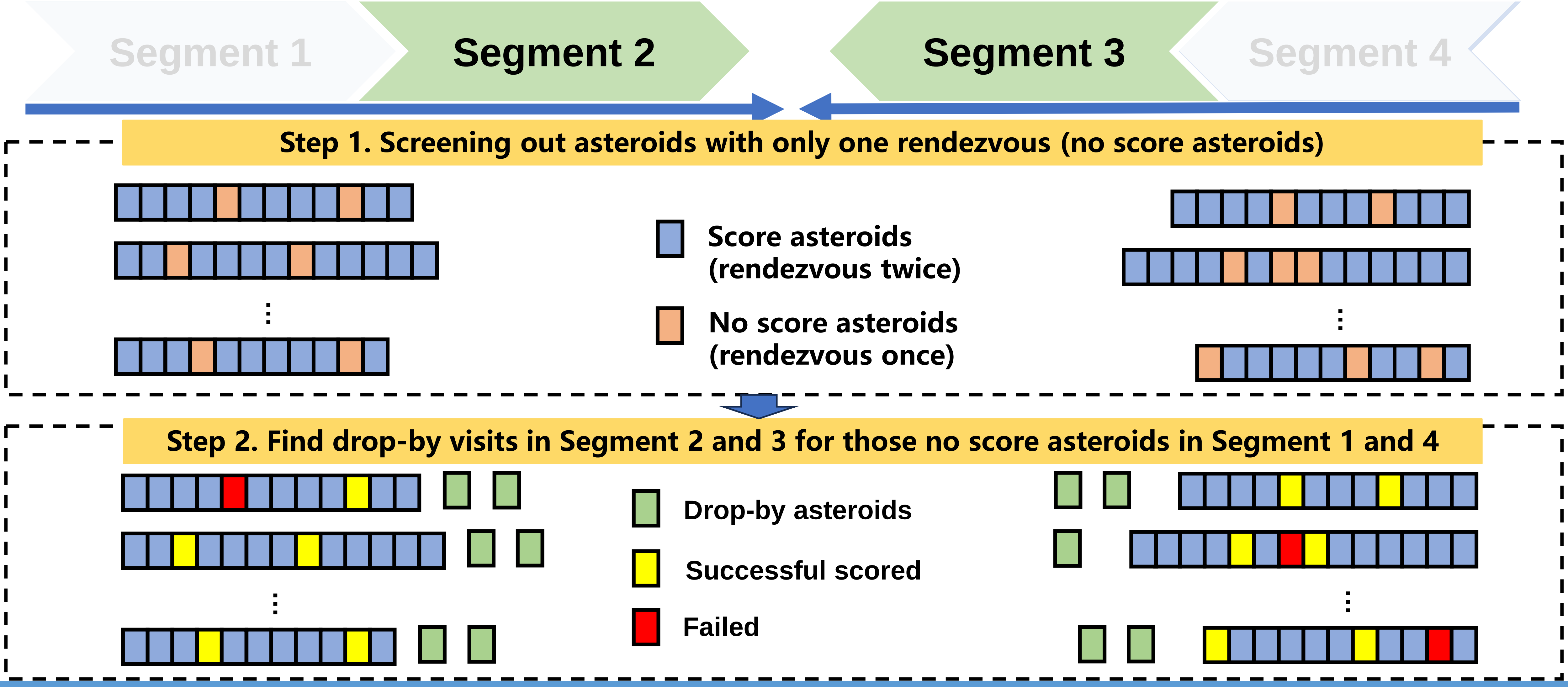
Segment 1
Segment 4

Add the output sequences to the set of selected sequences

Selected Segment 1 | **Selected Segment 4**

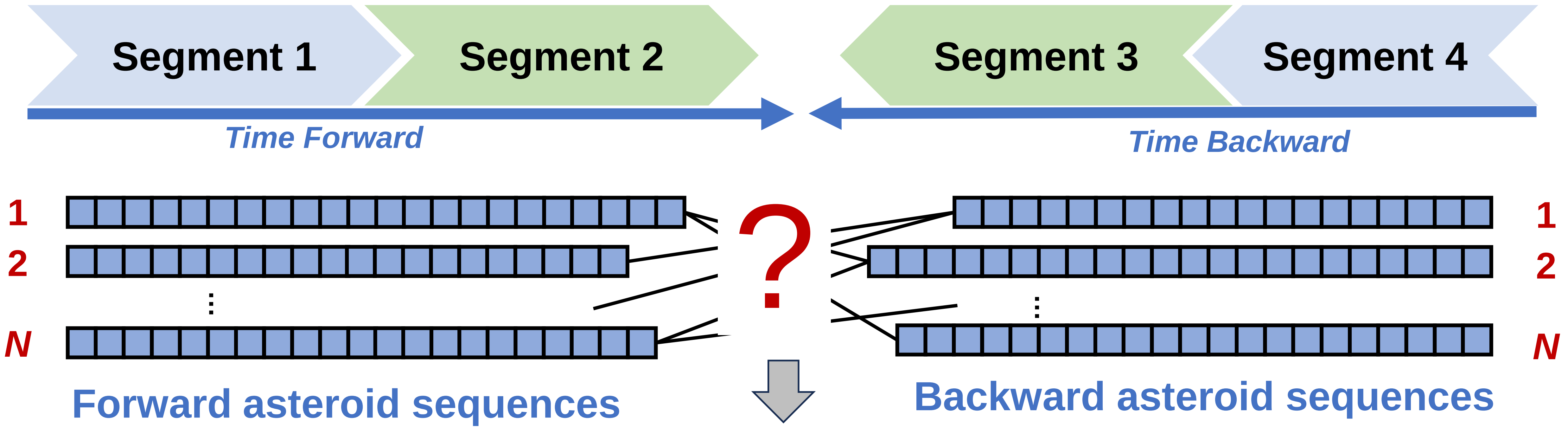
N

Segments 2 and 3 sequence candidates



Method: Asteroid visiting sequences

Matching forward and backward asteroid sequences



Matching Criteria

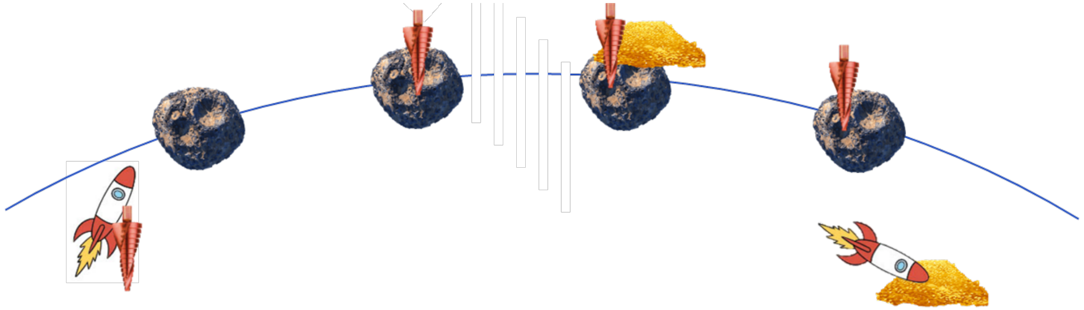
- Transfer cost is less than 8 km/s.
- The length of all sequences should be closely the same.

Method: Low-thrust trajectory converting

- There exists two main issues in the low-thrust trajectory generation.

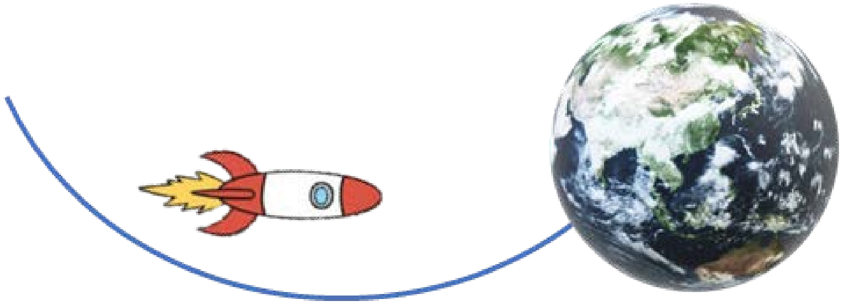
Problem 1: Low-thrust transfer infeasible

Due to the short transfer time of between asteroids, the low-thrust optimization problem is infeasible.



Problem 2: Constraints Violation

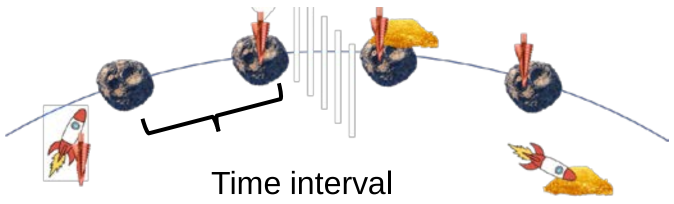
The fuel consumption of the trajectory violates the constraint requirements.



Method: Low-thrust trajectory converting

Steps for successful low-thrust trajectory converting

Step 1: Making low-thrust feasible

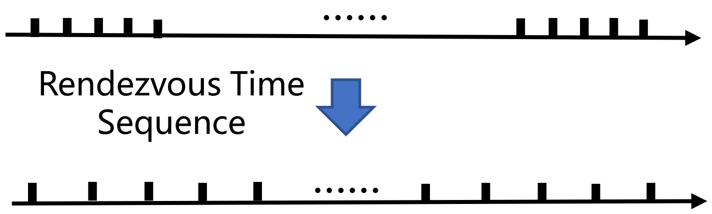


Increase the time interval for the infeasible interval

$$T_{k,i} = T_{k,i} \pm \delta T$$

Mining Mass ↓ 0.3 %

Step 2: Satisfying the fuel limitation

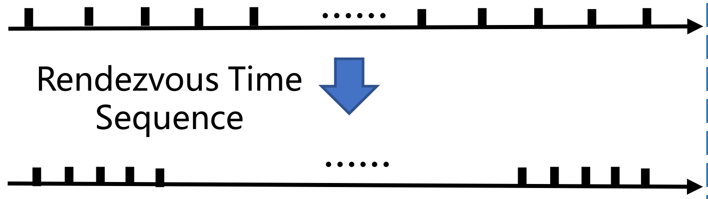


Find the most fuel-efficient direction and step size

$$T_{k,i} = T_{k,i} + D \cdot \Delta T_r^*$$

Mining Mass ↓ 1.1 %

Step 3: Maximizing the mining mass



Move nodes that are not sensitive to fuel consumption

$$\min(\{\Delta \mathrm{fuel}_i\}) \longrightarrow T_i$$

Mining Mass ↑ 0.4 %

Method Overview

DATABASE BUILDING

- Earth to Asteroid Database
- Asteroid to Earth Database
- Asteroid to Asteroid Database

ASTEROID SEQUENCES DETERMINATION

- Asteroid sequences for segments 1 and 4
- Drop-by asteroids for segments 2 and 3
- Matching forward and backward sequences

LOW-THRUST TRAJECTORY GENERATION

- Low-thrust trajectory converting
- Local optimization

Outline

1. Preliminary Analysis

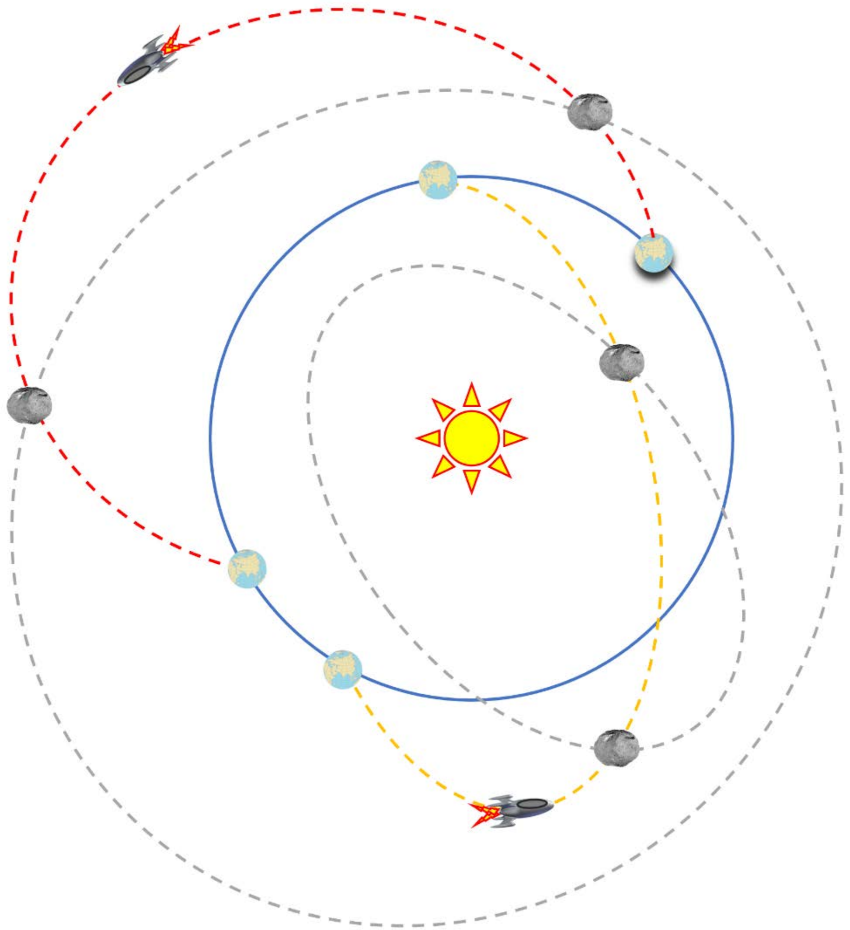
2. Method

2.1 Databases building

2.2 Asteroid visiting sequences searching

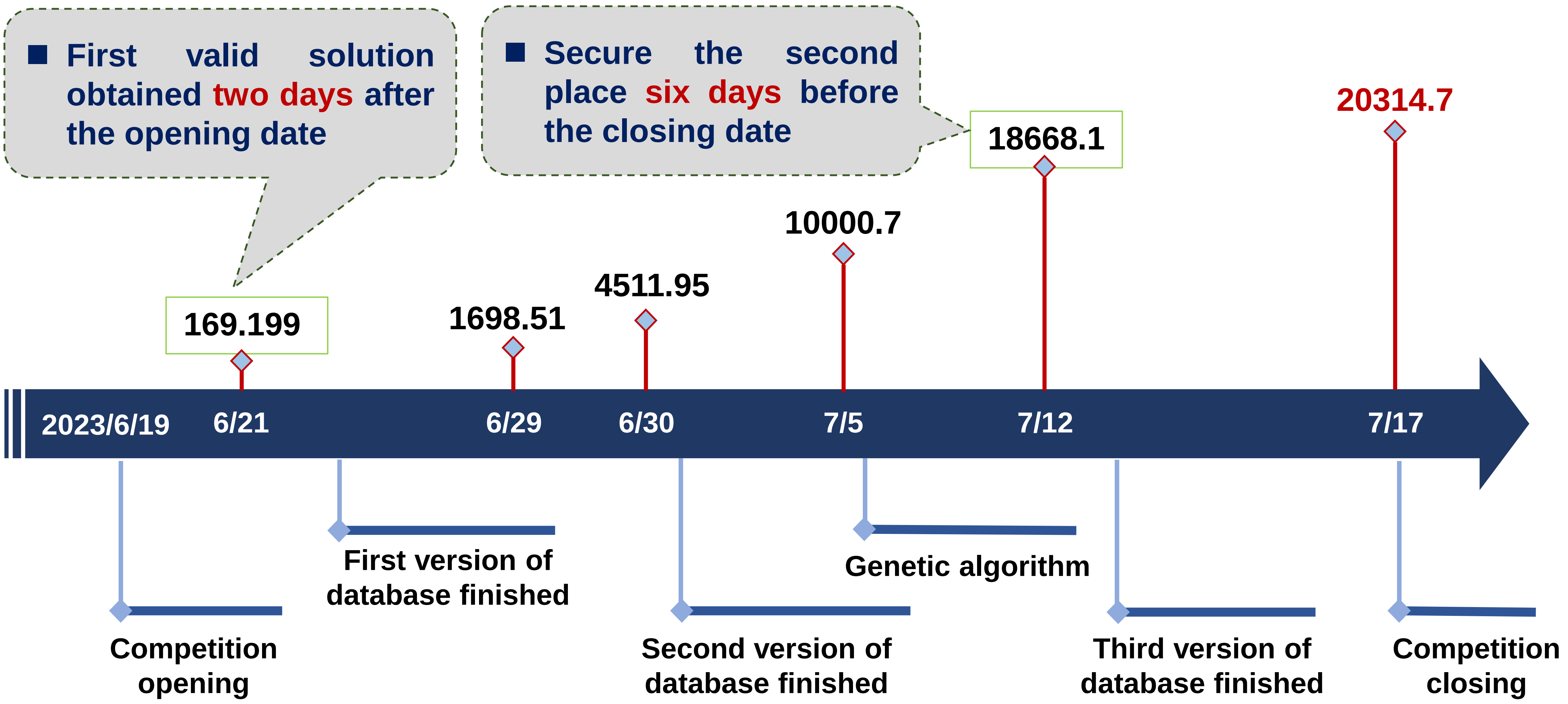
2.3 Low-thrust trajectory converting

3. Results and Discussion



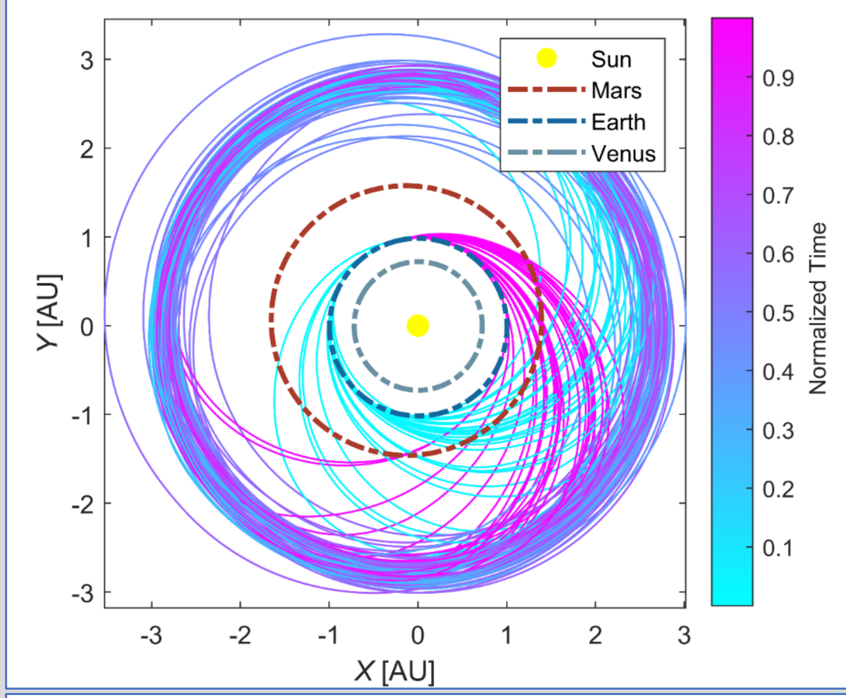
3 Results and Discussion

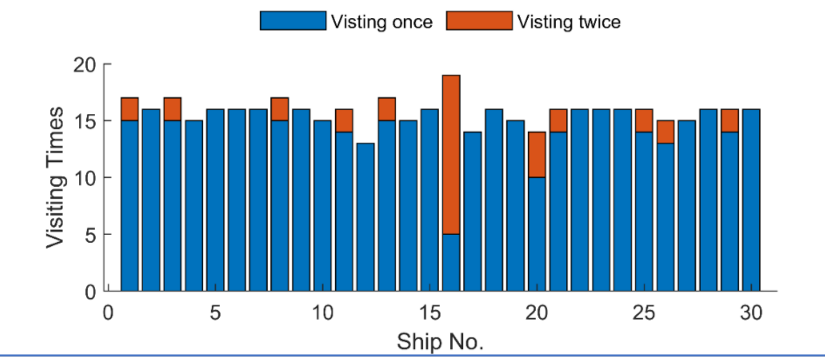
Timeline of the competition



Final submission

Mass retrieval	20,314.7 kg
Number of ships	30
Number of asteroids visited	237
Final score	17728

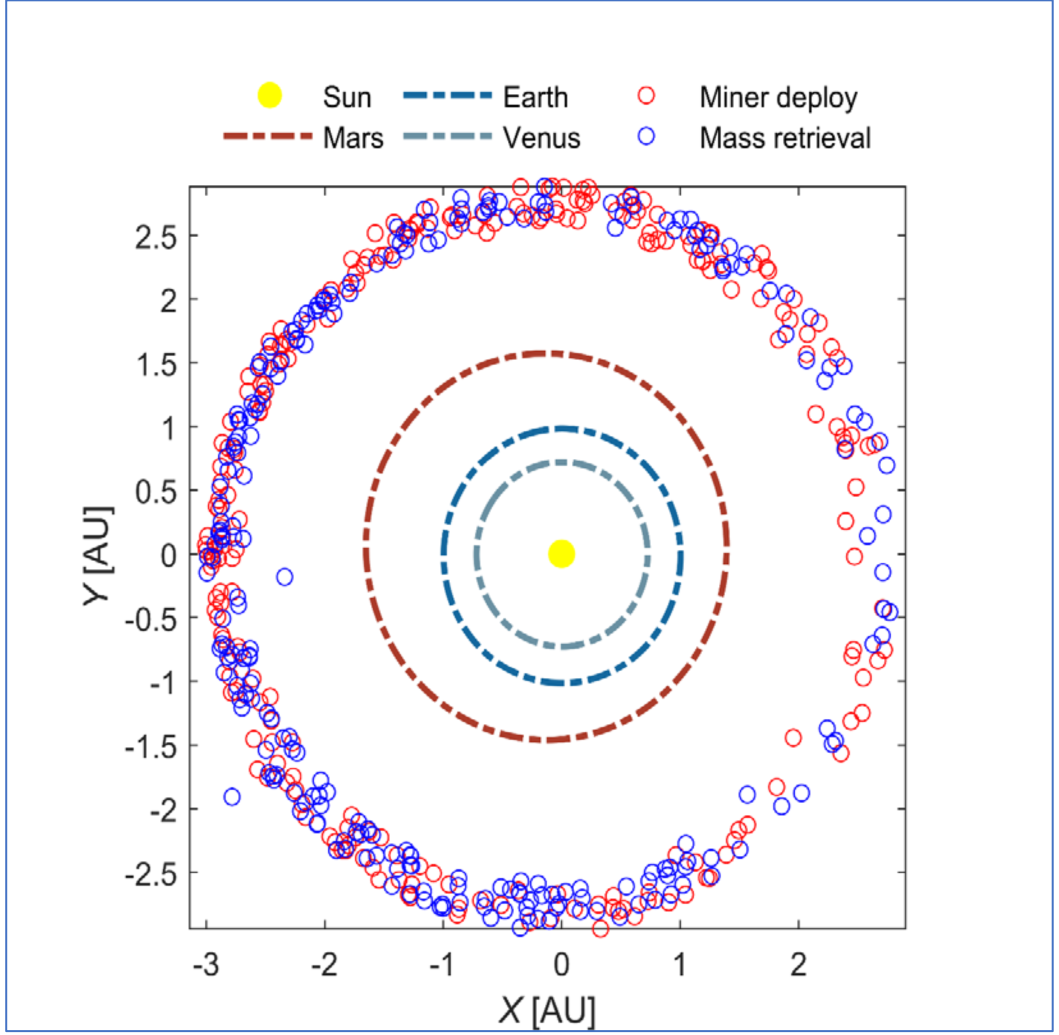


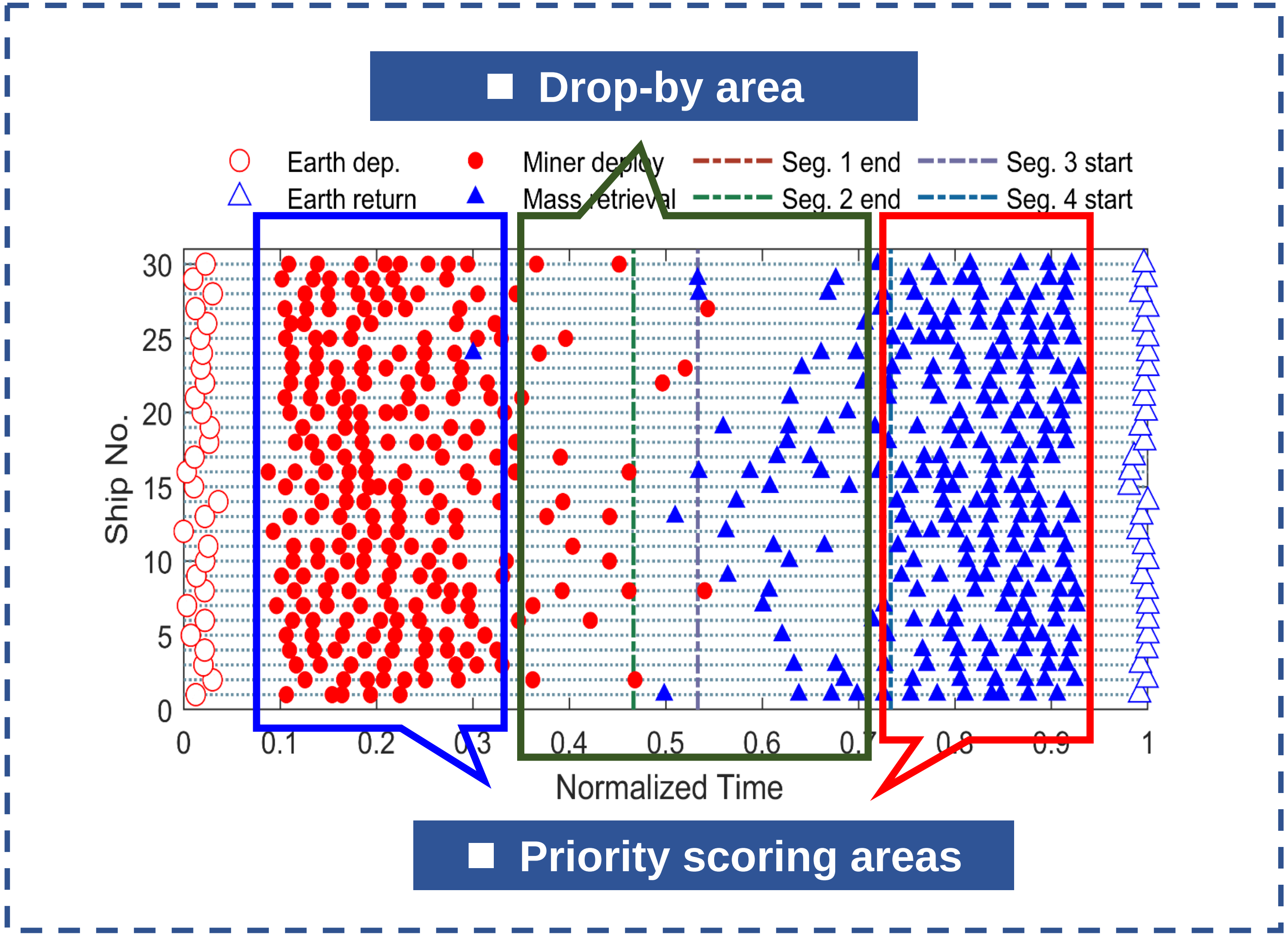


- No gravity assist was adopted

✓ Mining strategy 2 was used

◻ Asteroid visiting timeline

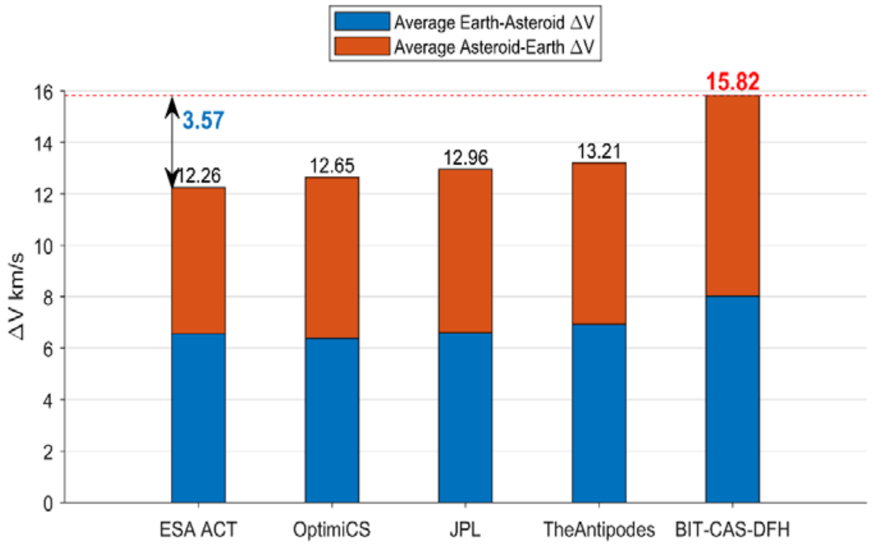




3 Results and Discussion

Comparison of top five teams

Team	Average mass retrieved/ asteroid [kg]	Average ΔV Earth-Asteroid [km/s]	Average ΔV Asteroid-Earth [km/s]	Average ΔV Asteroid-Asteroid [km/s]
JPL	80.5	6.60	6.36	2.13
BIT-CAS-DFH	85.7	8.02	7.80	2.17
OptimicS	82.8	6.38	6.27	2.46
ESA ACT	74.2	6.57	5.69	2.22
TheAntipodes	79.3	6.93	6.28	2.38



3.5 km/s more than the average
for the departure Earth-asteroid and return asteroid-Earth transfers

Summary

✓ Positives treatments:

- We have appropriately divided the mission into different phases
- We have chosen mining strategy 2
- We used four segments strategy for searching asteroid sequences

✓ Negative issues:

- Too much fuel consumed for the departure Earth-asteroid and return asteroid-Earth transfers
- At least one more asteroid can be visited for each ship if the departure and return legs were properly optimized.
- If we managed to bring only 40 kg on this asteroid, the permissible number of ships can reach to the same level with JPL.

China Trajectory Optimization Competition (CTOC) was initiated in 2009

Our team won the championship of CTOC-12

We will launch CTOC-13 in this summer

The problem will focus on on-orbit servicing

CTOC started in 2009

CTOC-12 in 2022

CTOC-13 coming soon

WELCOME TEAMS ALL OVER THE WORLD TO JOIN CTOC-13 !!