清華大學航天航空学院
School of Aerospace Engineering, Tsinghua University
航天动力学与控制实验室
Laboratory of Astrodynamics

Sustainable Asteroid Mining

GTOC12 Summary

Presenter: Zhong Zhang

Announcements

The winner: Tsinghua University and Shanghai Institute of Satellite Engineering.

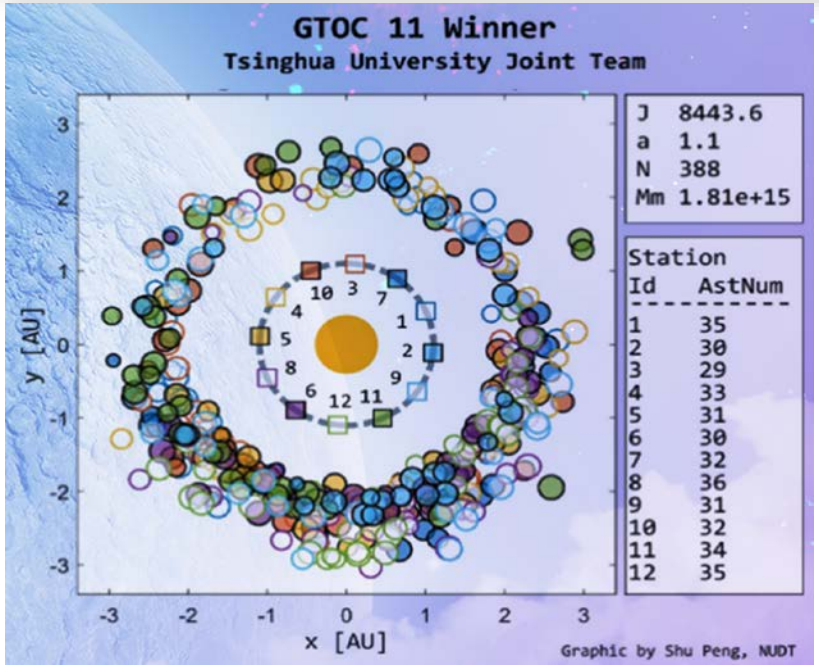
Congratulations to the joint team of Tsinghua University and Shanghai Institute of Satellite Engineering for winning the 11th Global Trajectory Optimisation Competition (GTOC 11)! A new GTOC champion team, led by Zhong Zhang and Haiyang Li, with members Nan Zhang, Xiang Guo, Di Wu, Xuan Xie, Jinyuan Li, Jia Yang, Shiyu Chen, Fanghua Jiang, Hexi Baoyin (Tsinghua University), and Huixin Zheng, Xiaowen Duan (Shanghai Institute of Satellite Engineering), is born. Very well done!

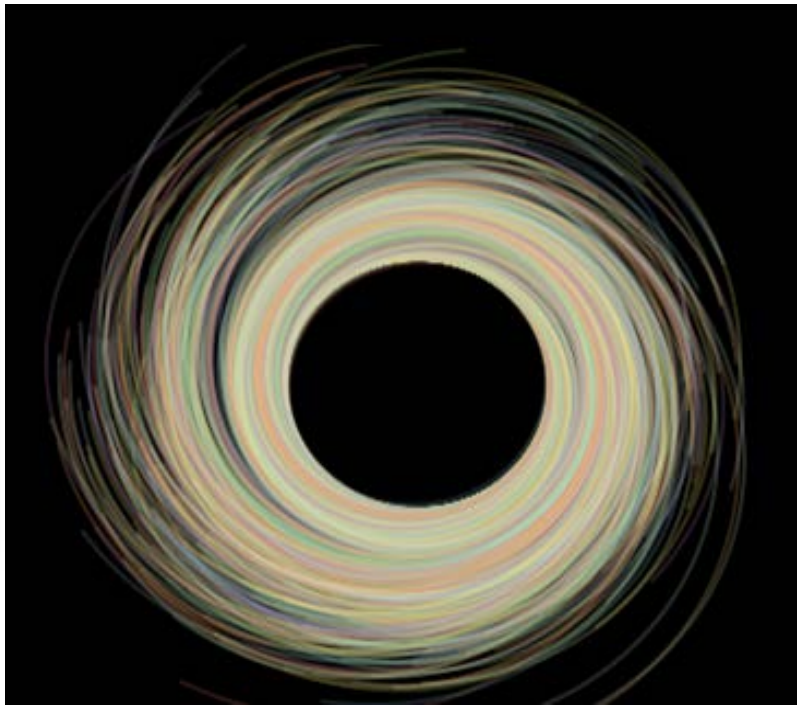
Congratulations also to ESA Advanced Concepts Team and their Friends (led by Dario Izzo and Chit Hong Yam), and the joint team of University of Auckland, ISAE-SUPAERO, University of Surrey and University of Southampton (led by Roberto Armellin) for winning the second and third places, respectively.

Many thanks to everyone who participated and helped make this competition a big success. For discussion purposes, the champion team's solution is presented in the following, and other teams' solutions will be presented later.

GTOC 11 Winner

Tsinghua University Joint Team





Leaderboard

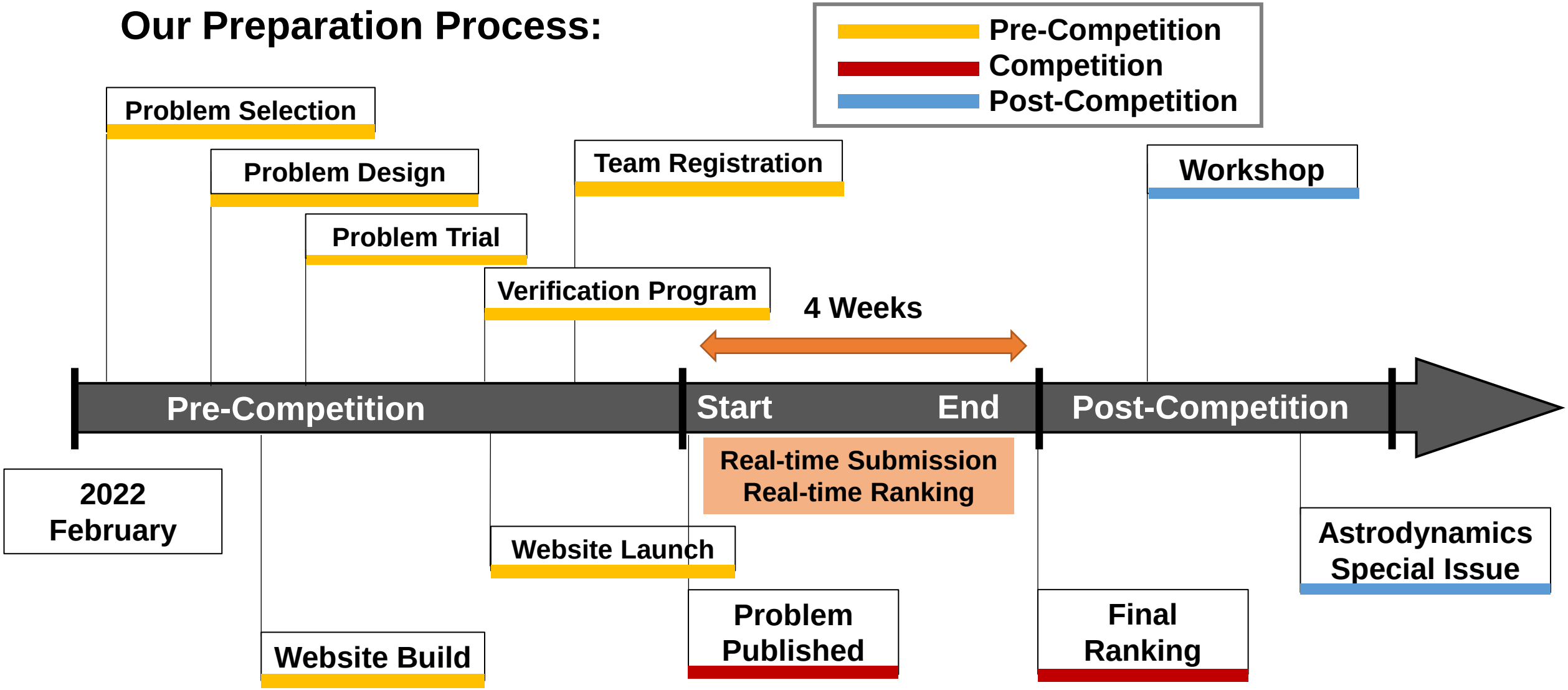
Start ranking at 12 PM UTC, 17 October

Name	Submissions	Last Submission	Best Submission	Mmin, N	Best Score
Tsinghua	11	Nov 07, 2021 11:10 AM UTC	Nov 07, 2021 11:10 AM UTC	1.81364e+15, 388	8443
ACT&Friends	5	Nov 07, 2021 2:30 AM UTC	Nov 06, 2021 6:46 PM UTC	2.0125e+15, 301	6359
theAntipodes	44	Nov 07, 2021 8:14 AM UTC	Nov 07, 2021 8:14 AM UTC	1.27672e+15, 293	5992
UT Austin	5	Nov 07, 2021 6:48 AM UTC	Nov 07, 2021 6:48 AM UTC	1.13283e+15, 235	5885.469300
ASRL	34	Nov 07, 2021 4:43 AM UTC	Nov 07, 2021 4:43 AM UTC	1.10046e+15, 209	5525.388800
The Eccentric Anomalies	12	Nov 07, 2021 11:39 AM UTC	Nov 07, 2021 11:39 AM UTC	1.89224e+15, 346	5487.543400

Happy to take the responsibility (also the burden) to host GTOC12!

Our GTOC12 Schedule

Our Preparation Process:



Problem Design

Principle

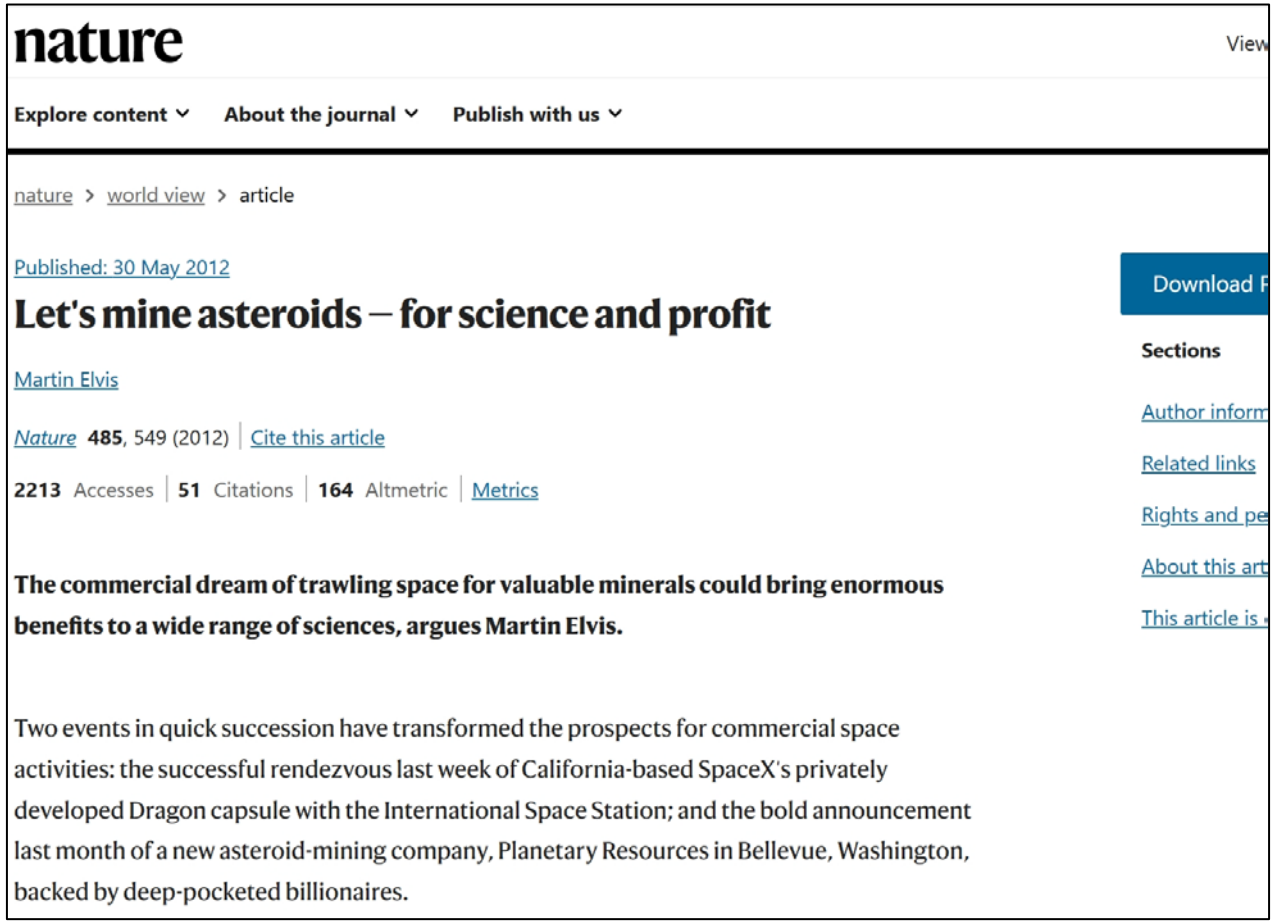
- **Understandable**: simple enough so that other field experts can get involved
- **Complex**: complex enough to differentiate teams of different levels
- **Innovation**: no available software and algorithms can fully solve the problem

- 19 topics across 5 major aspects:
- "Cooperative Planetary Defense" was once considered as a competition topic but was later abandoned.
- "Asteroid Mining" is finally chosen.

- Izzo, D., Maertens, M. The KesslermRun: on the design of the GTOC9 challenge. Acta Futura, 2018, 11: 11--24, doi:10.5281/zenodo.1139022.
- Petropoulos, A. E., Gustafson, E. D., Whiffen, G. J. GTOC X: settlers of the galaxy problem description and summary of the results. 2019 AAS/AIAA Astrodynamics Specialist Conference Portland, ME, paper AAS 19-891, 2019.
- Shen, H., Luo, Y., Zhu, Y., Huang, A. Dyson sphere building: On the design of the GTOC11 problem and summary of the results. Acta Astronautica, 2023, 202: 889--898, doi:10.1016/j.actaastro.2022.08.040.

The Problem of the 12th Global Trajectory Optimization Competition

Sustainable Asteroid Mining



nature

View

Explore content ⌄ About the journal ⌄ Publish with us ⌄

nature > world view > article

Published: 30 May 2012

Let's mine asteroids – for science and profit

Martin Elvis

Nature **485**, 549 (2012) | Cite this article

2213 Accesses | **51** Citations | **164** Altmetric | Metrics

Download F

Sections

Author inform

Related links

Rights and pe

About this art

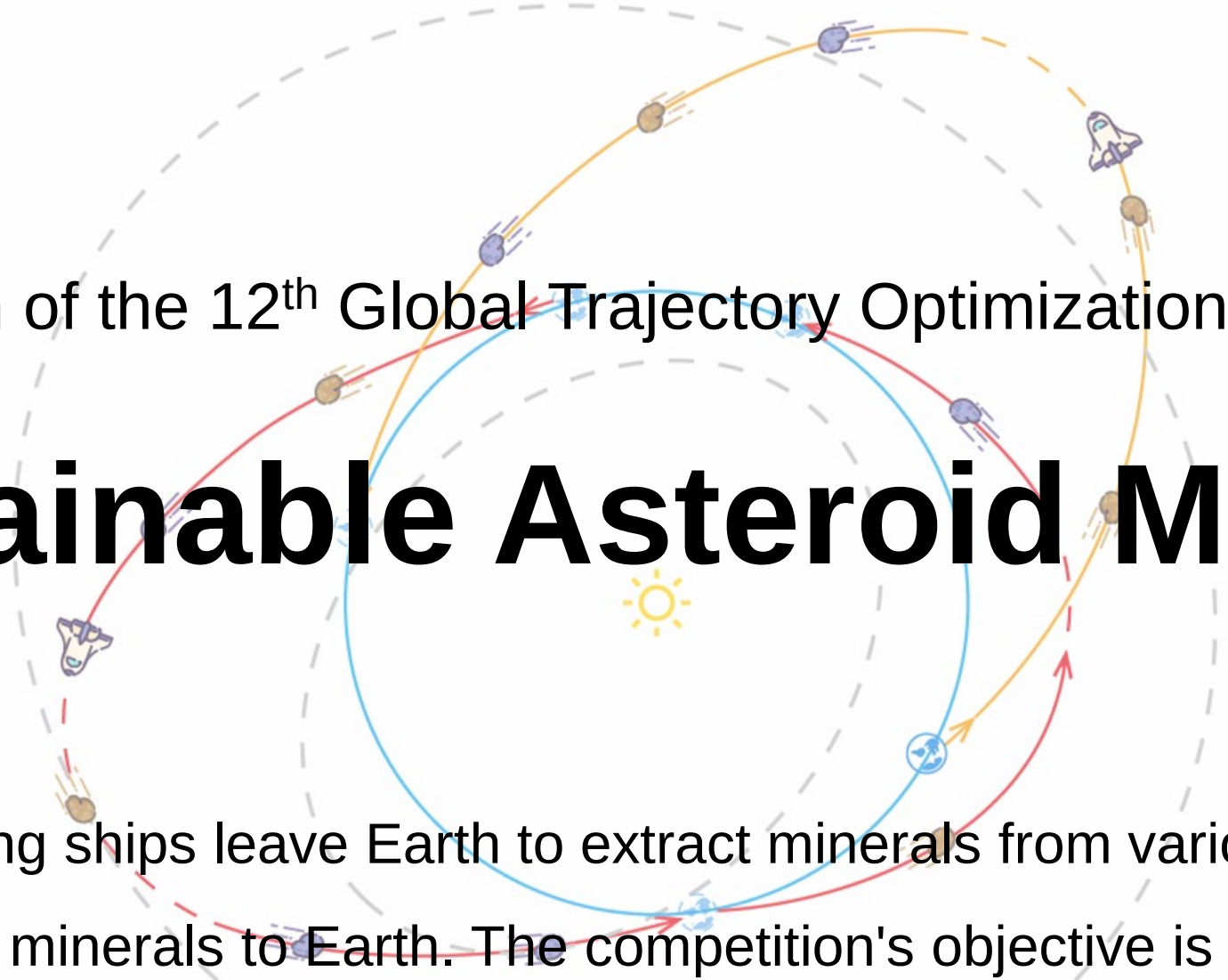
This article is

The commercial dream of trawling space for valuable minerals could bring enormous benefits to a wide range of sciences, argues Martin Elvis.

Two events in quick succession have transformed the prospects for commercial space activities: the successful rendezvous last week of California-based SpaceX's privately developed Dragon capsule with the International Space Station; and the bold announcement last month of a new asteroid-mining company, Planetary Resources in Bellevue, Washington, backed by deep-pocketed billionaires.

The Problem of the 12th Global Trajectory Optimization Competition

Sustainable Asteroid Mining



Multiple mining ships leave Earth to extract minerals from various asteroids and return the minerals to Earth. The competition's objective is to optimize for the maximum total mass of mined resources. Teams need design the trajectories for all mining ships.

GTOC12: Sustainable Asteroid Mining

Multi-Ship Asteroid Mining

Interpretation:

① **Mining is simplified to two rendezvous**: The longer the mining time (interval between two meetings), the more minerals are extracted.

② **Main Belt and Near-Earth Asteroids**

③ **Dynamical model**: 2-body, low thrust. Venus, Earth, and Mars gravity assists feasible. The mission duration is 15 years (starting in 2035).

④ **Maximum Flyby Speed Limit:** 6 km/s

⑤ **Number of Ships Constraint**: The number of ships is constrained by the average mining mass per ship.

⑥ **Game Model**: The more mining that occurs, the lower the score becomes.

Highlights:

- **Game Model in real time**
- **Coupled Multiple Spacecraft Trajectories**

Problem Design

Problem Analysis and Parameter Design: Multi-Ship Asteroid Mining

Some trails ⇓ **Simplification**

Impulse Simplification: Initially, an impulse design is adopted, with fuel consumption corrected by a multiplication of an experience coefficient (usually 1.5).

Ignoring Intermediate Maneuvers: All midway maneuvers of spacecraft are prohibited. Instead, maneuvers are only conducted when leaving and arriving at asteroids.

Beam Search as a benchmark: employed when optimizing sequences

As a result, our prediction for the optimal solution is about 750-800kg per ship

Sustainable Asteroid Mining: on the design of GTOC12 problem and summary of the results

Problem Design

Game Model Design:

Principle

- **No loopholes**: avoid creating loopholes that cause harm to all teams.
- **No offline alliance**: prevent different teams from forming alliances
- **Strength stand out**: ranking determined by the level of their design, rather than gaming bonus.
- **Diversity**: game model should encourage a diversity of solutions.

Guessing Chain?

What would happen if the game model encouraged teams to submit solutions to claim specific mining asteroids and did not penalize their subsequent submissions?

Problem Design

Game Model Design：

Conservative Parameters

For the same result (mining 100kg), submissions lead to different reductions:

- 1 submission reduces by 11%,
- 2 submissions reduce by 14%,
- 10 submissions reduce by 22%,
- 100 submissions reduce by 31%.

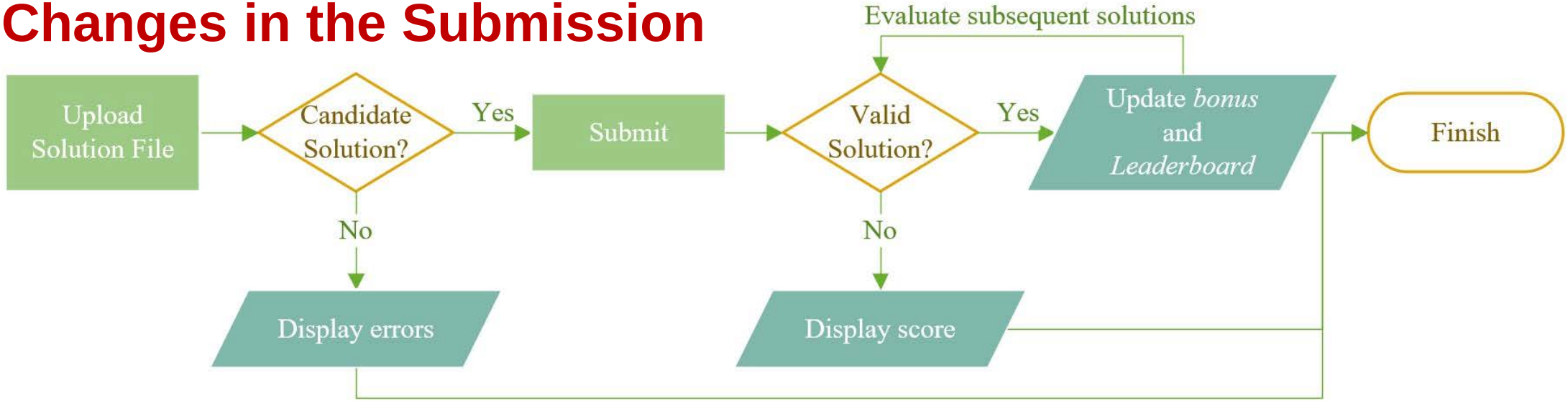
Offline verification program

Windows: VS 2012

Linux: GCC 10.3.2

MacOS: M series Intel

Changes in the Submission



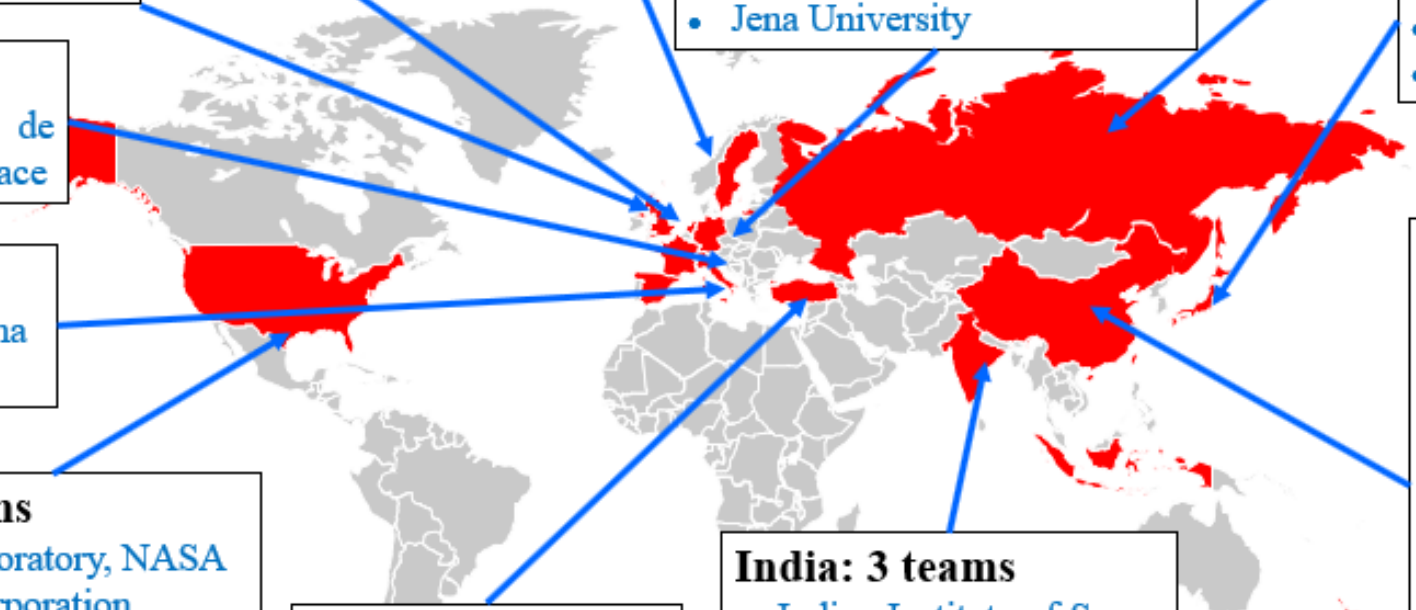
General Information：

- **Web：https://gtoc12.tsinghua.edu.cn/**
- **Time：2023.6.19~7.17**
- **Status：102 teams registered, with 28 teams submitting results.**
- **Winner：NASA JPL**
- **Astrodynamics Special Issue**

Official GTOC12 website
https://gtoc12.tsinghua.edu.cn/

Official GTOC website
https://sophia.estec.esa.int/gtoc_portal/

Distribution of participating teams



Netherlands: 3 teams
- European Space Agency
- Delft University of Technology

Sweden
- KTH Royal Institute of Technology

Russia: 2 teams
- Russian Academy of Sciences

England:
- University of Surrey

Germany:
- Technical University Munich
- Jena University

Japan:
- JAXA
- University of Tokyo

France: 3 teams
- Institut Supérieur de l'Aéronautique et de l'Espace

China: 29 teams
- Chinese Academy of Science
- Beihang University
- Beijing Institute of Technology
- Beijing Aerospace Control Center
- National University of Defense Technology
- Harbin Institute of Technology
- Nanjing University of Aeronautics and Astronautics
- Xi'an Satellite Control Center

Italy: 4 teams
- Sapienza Università di Roma
- University of Trento

America: 14 teams
- Jet Propulsion Laboratory, NASA
- The Aerospace Corporation
- The University of Texas at Austin
- Auburn University

India: 3 teams
- Indian Institute of Space Science and Technology

Turkey:
- Space Technologies Research Institute

New Zealand:
- University of Auckland

Discussion on teams' solutions

Top 20 Teams:

- **Clear Distinction Among Teams**
- **Game model led to ranking changes, but the impact was not significant.**
- **New participants joined and achieved commendable performance: OptimiCS (3rd place) and ATQ (8th place).**

GTOC 12 Winner: NASA JPL

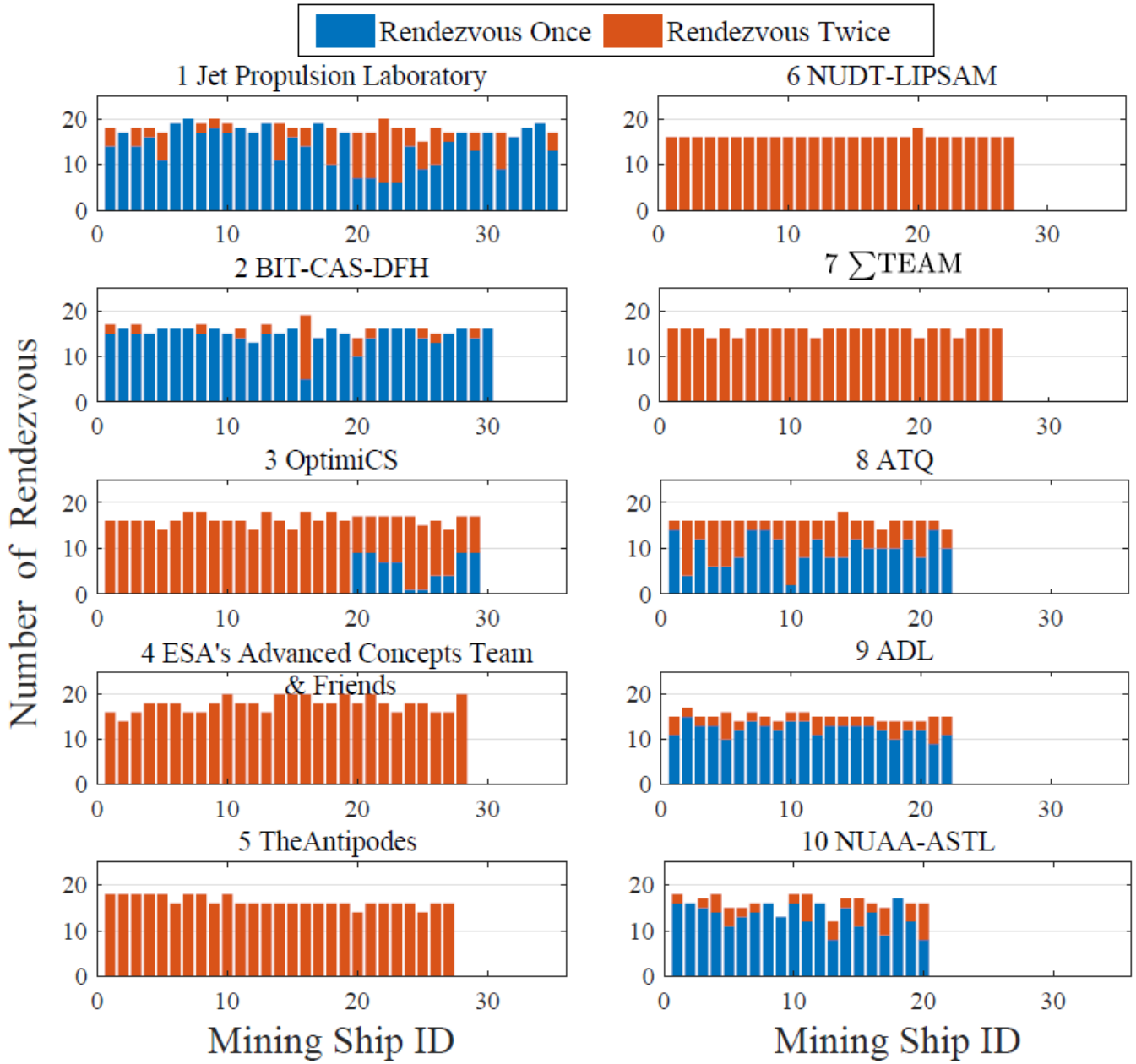
Congratulations to Team **Jet Propulsion Laboratory** for securing the championship title with their incredible solution at the close of GTOC 12! Well Done to the team leaders, Anastassios Petropoulos and Gregory Lantoine, with members Austin Nicholas, Tim McElrath, Zubin Olikara, Sungmoon Choi, Etienne Pellegrini, Damon Landau, Drew Jones, Vishala Arya, Try Lam, Thomas Pavlak, Yuji Takubo, Quinn Kostelecky, CK Venigalla, Brian Anderson, Kenza Boudad, Mark Wallace, Dimitri Gerasimatos, and Jon Sims.

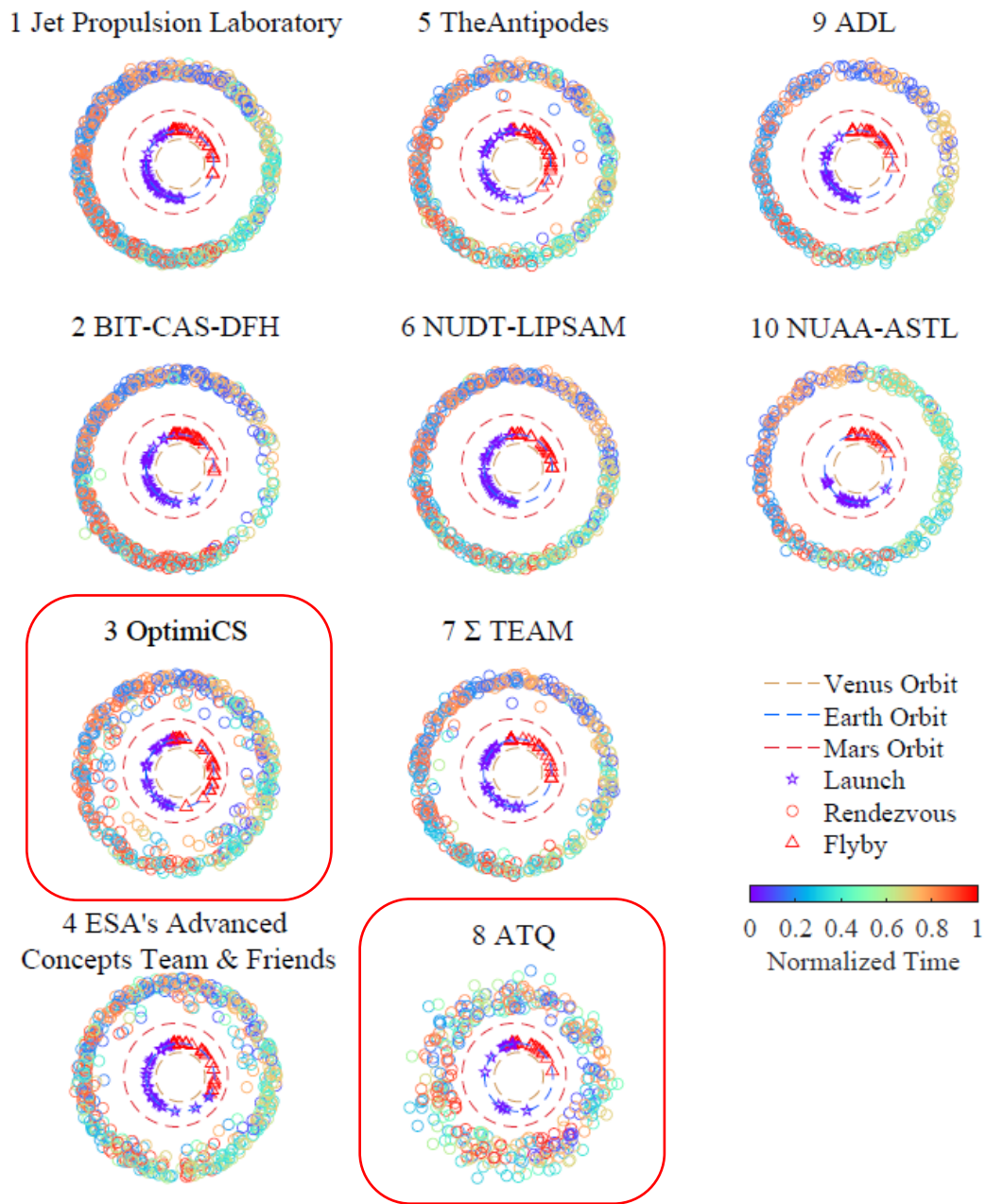
Congratulations are also in order for the joint team **BIT-CAS-DFH** led by Shengmao He, Chao Peng, Yang Gao (CSU, CAS), Changxuan Wen (Beijing Institute of Technology), Zhengfan Zhu (DFH Satellite Co., Ltd), and Yang Zhang (AIR, CAS), as well as the team **OptimiCS** led by Vincent Debout and Sébastien Goulet (CS Group) for securing the second and third places, respectively.

Many thanks to all the teams for your participation and unwavering dedication. Each team showcased remarkable skill and effort throughout the competition, making it a resounding success. The diagram below illustrates the solution proposed by the winning team:

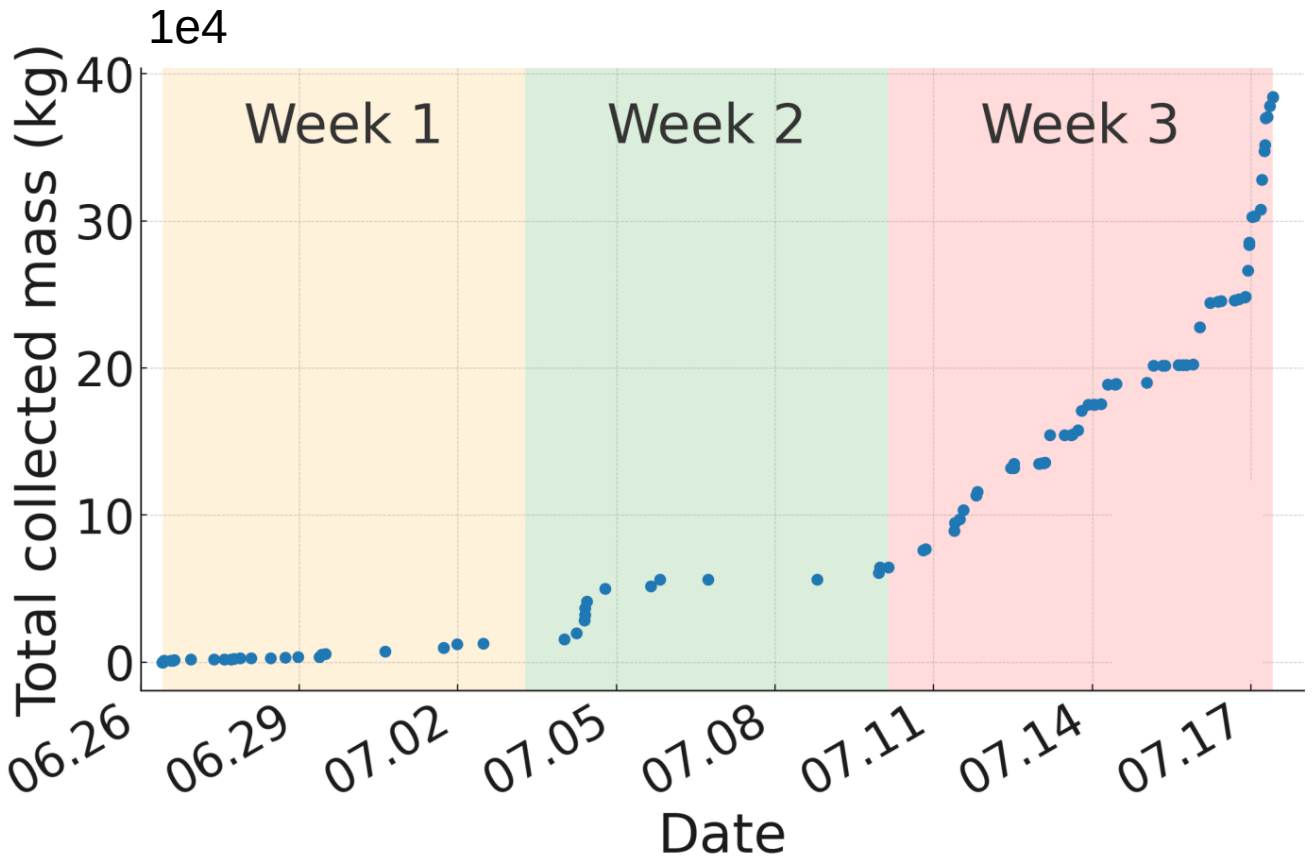
Rank	Team Name	N_{ship}	N_{ast}	$\sum \bar{M}$ (kg)	J (kg)
1	Jet Propulsion Laboratory	35	313	25193	22533
2	BIT-CAS-DFH	30	237	20315	17728
3	OptimiCS	29	236	19531	17082
4	ESA's Advanced Concepts Team & Friends	28	249	18475	15728
5	TheAntipodes	27	222	17614	15489
6	NUDT-LIPSAM	27	217	17592	15161
7	∑TEAM	26	203	16717	14714
8	ATQ	22	175	13352	13106
9	ADL	22	165	13193	12062
10	NUAA-ASTL	20	161	11514	10667
11	The Aerospace Corporation	15	105	7769	7565
12	vacuum cleaner could do better	12	74	5384	5354
13	The Mean Anomalies	15	75	5532	4573
14	HIT	10	51	4297	4037
15	Set sail in space	10	60	4182	4004
16	Team Jena	10	41	4211	3584
17	NJU-LESEC-DSEL	8	31	2870	2442
18	Dust	5	15	1538	1265
19	Hit-anobody	4	8	727	707
20	ACELab	3	9	695	627

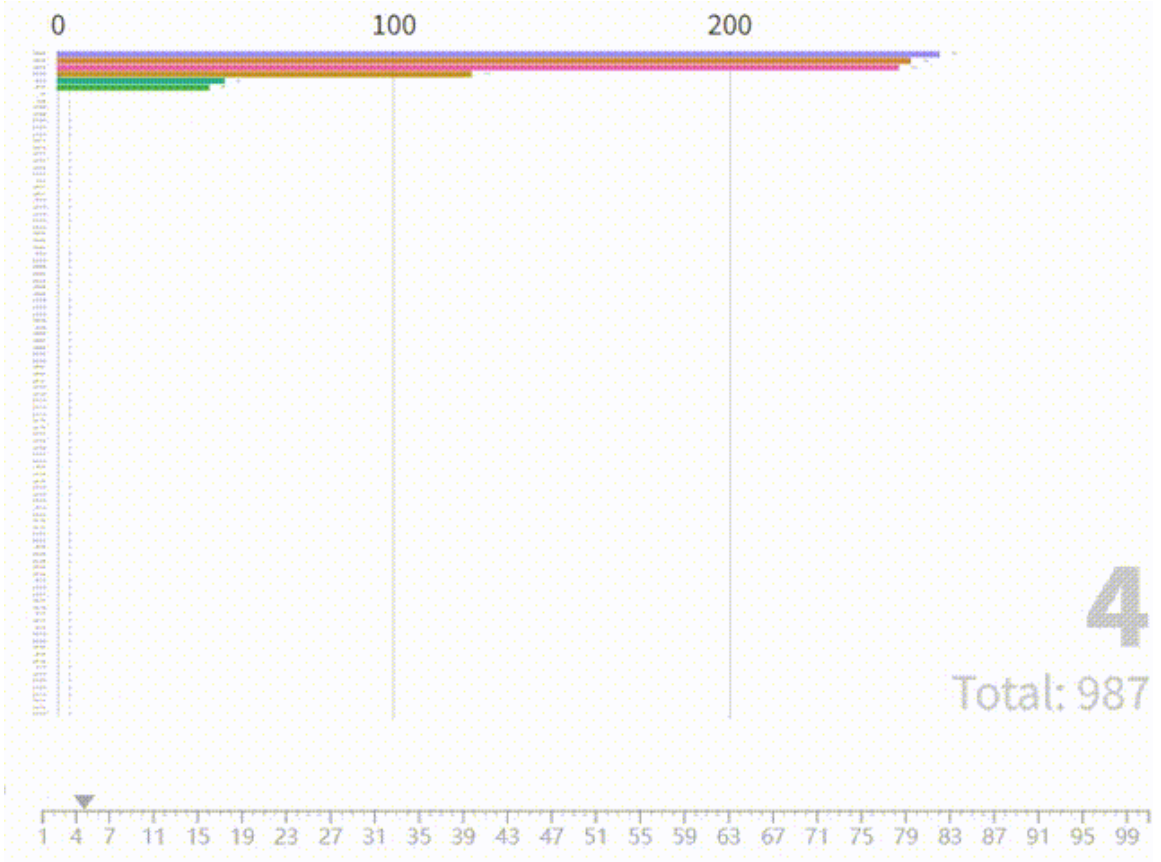
Top 10 teams' solutions





Effects of the Game Model:





A total of 101 submissions were made, collectively mining 400 tons of minerals.

Conclusion

- GTOC12 attracted over a hundred teams for the first time, continuing to expand the GTOC influence.
- GTOC12 introduced a game model and provided an offline verification program for the first time in GTOC history.
- GTOC13 will be hosted by NASA JPL, and Tsinghua is looking forward to participating it!

Zhong Zhang, Nan Zhang, Xiang Guo,
Di Wu, Xuan Xie, Jia Yang,
Fanghua Jiang, Hexi Baoyin
Email: zhong-zh19@mails.tsinghua.edu.cn