国防科学技术大学
National University of Defense Technology

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GTOC9-Results from NUDT

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Outline

1.Problem Analysis

2.Our Approach

3.Our History and Results

4. Discussions

1. Problem Analysis

◆ GTOC9 Problem

➢ Kessler run: remove 123 orbiting debris within 8 years (ergodic rendezvous with a series of missions)

➢ Design lowest costs missions

- minimize the total mission numbers (essential)
- minimize the fuel costs for each mission (important)

$$J = \sum_{i=1}^{n} C_i = \sum_{i=1}^{n} \left[c_i + \alpha \left(m_{0_i} - m_{dry} \right)^2 \right]$$

$$c_i = c_m + \frac{t_{submission} - t_{start}}{t_{end} - t_{start}} (c_M - c_m)$$

1. Problem Analysis

◆ Problem Analysis

- It's similar to the **Dynamic TSP**
- To find the optimal removal plan, the following three sub-problems must be addressed:

1） How to plan the successive removal missions?

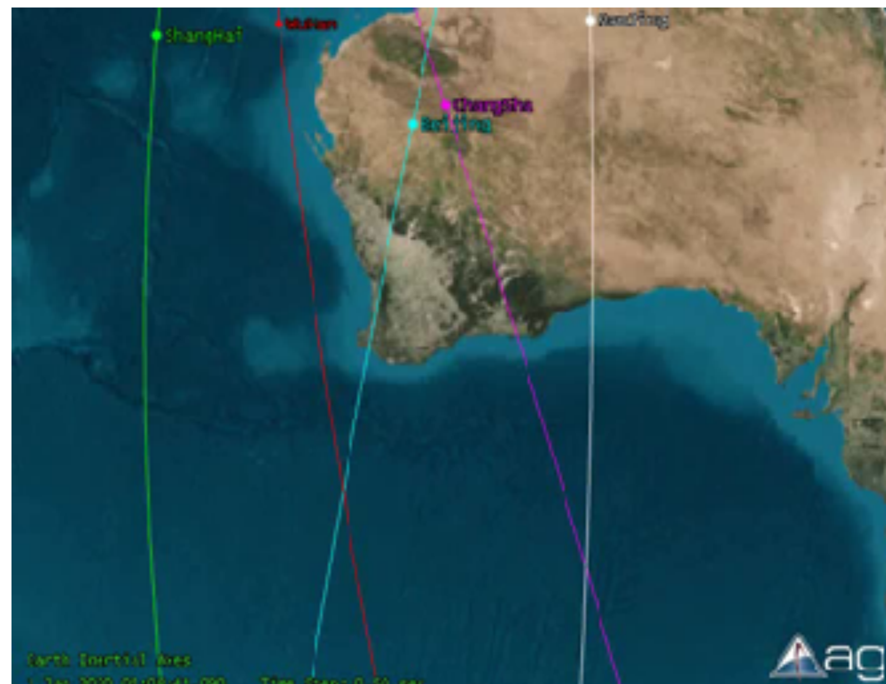
2） How to minimize the cost of a single mission?

3） How to optimize the trajectory between each two debris?

1. Problem Analysis

(1)How to plan the successive removal missions?

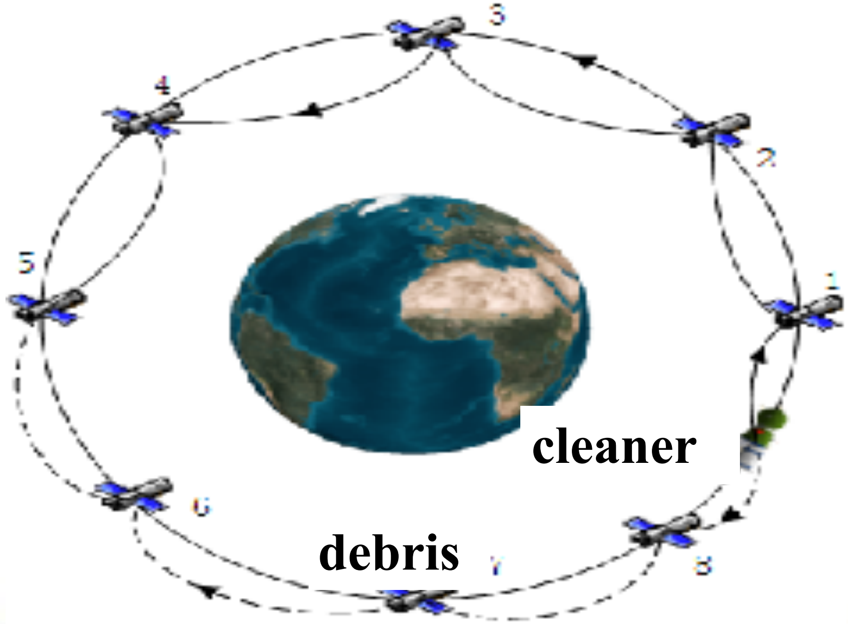
- **Large-scale TSP problem**
- **Time-dependent debris position make more complex and difficult**



1. Problem Analysis

(2)How to minimize the cost of a single mission?

- It's a mixed-integer nonlinear-programming problem
- The sequence (integer variables) and the transfer time (real variables) between each two debris need to be optimized simultaneously.



1. Problem Analysis

(3) How to optimize the trajectory between each two debris?

- Difficult to **quickly estimate** the cost ΔV and the flight time Δt with high precision
- Difficult to find the optimal solution for the **long-duration** (especially for > 25 day).

Manned Spaceflight

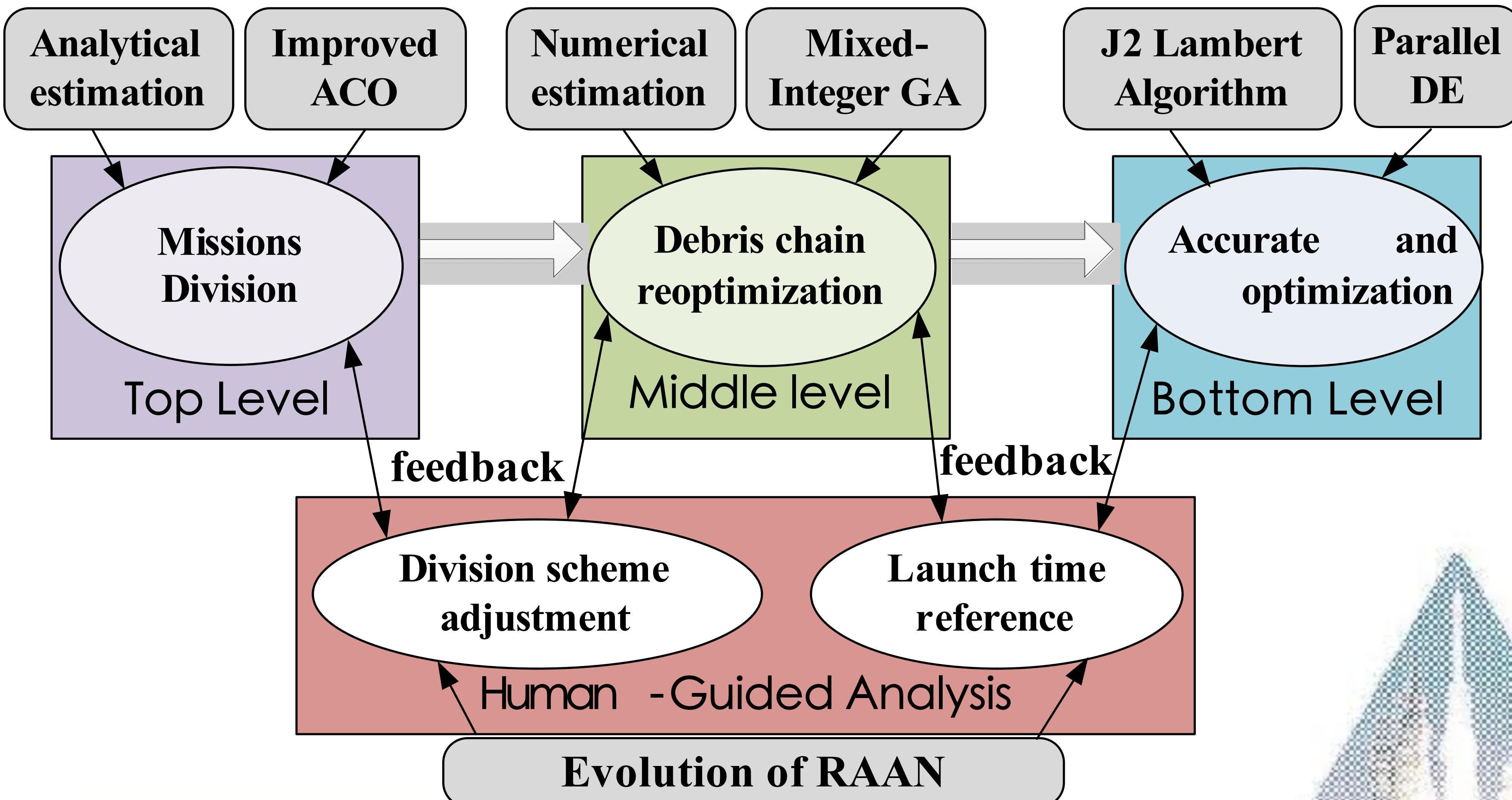
- Time: 2-3 days
- Nearly coplanar

Debris Removal

- Time: 5-30 days
- Large non-coplanar

2. Our Approach

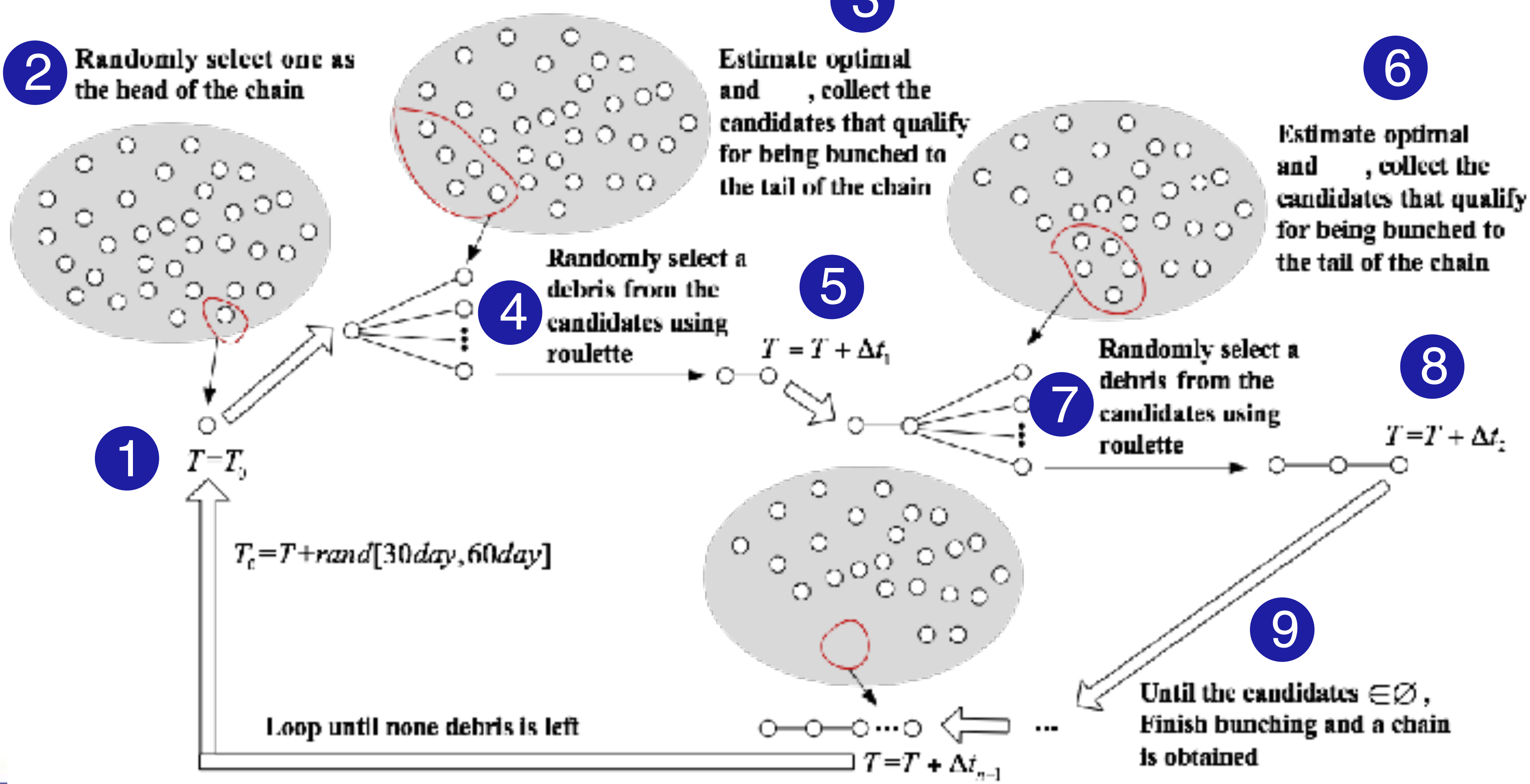
◆ Framework of the approach



2. Our Approach

◆ Algorithm 1: ACO for bunching debris chain

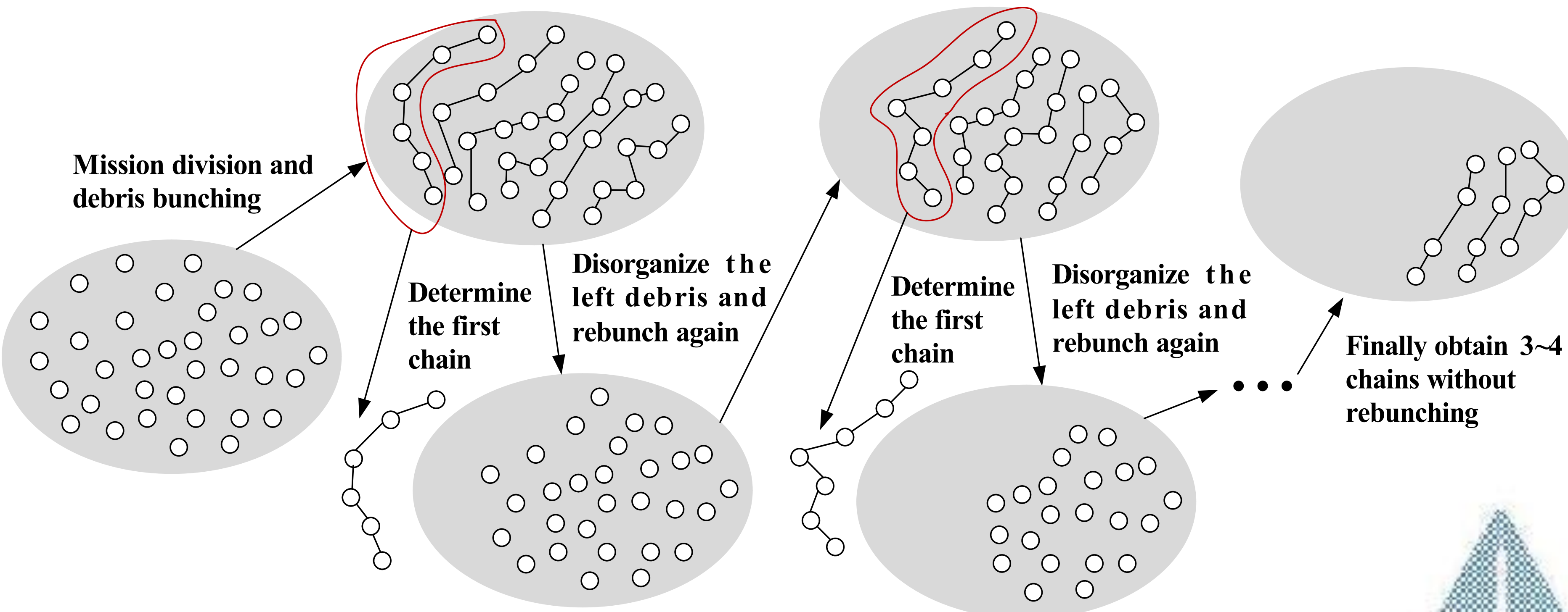
- **Solution construction method**



2. Our Approach

◆ **Algorithm 1: ACO for bunching debris chain**

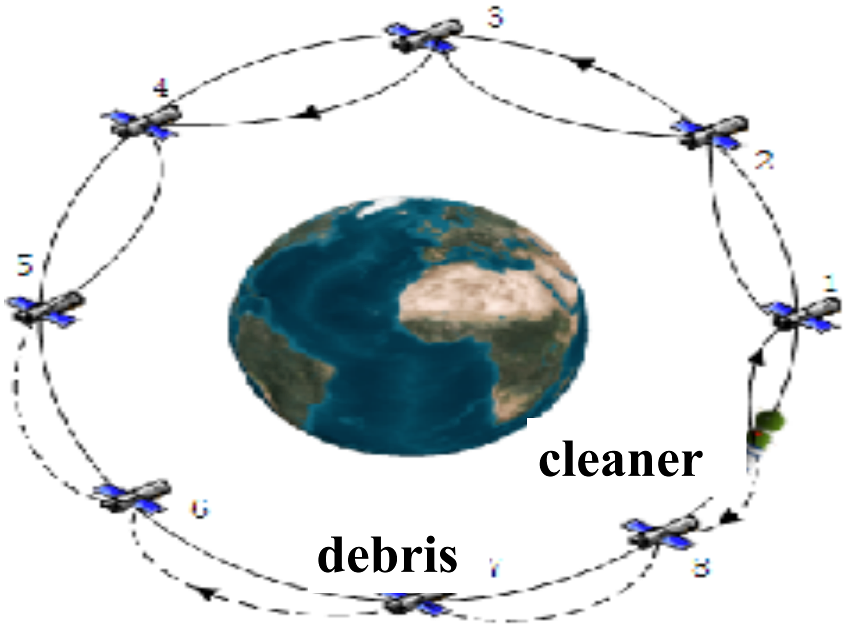
- **Solving approach: determine the chains one by one**

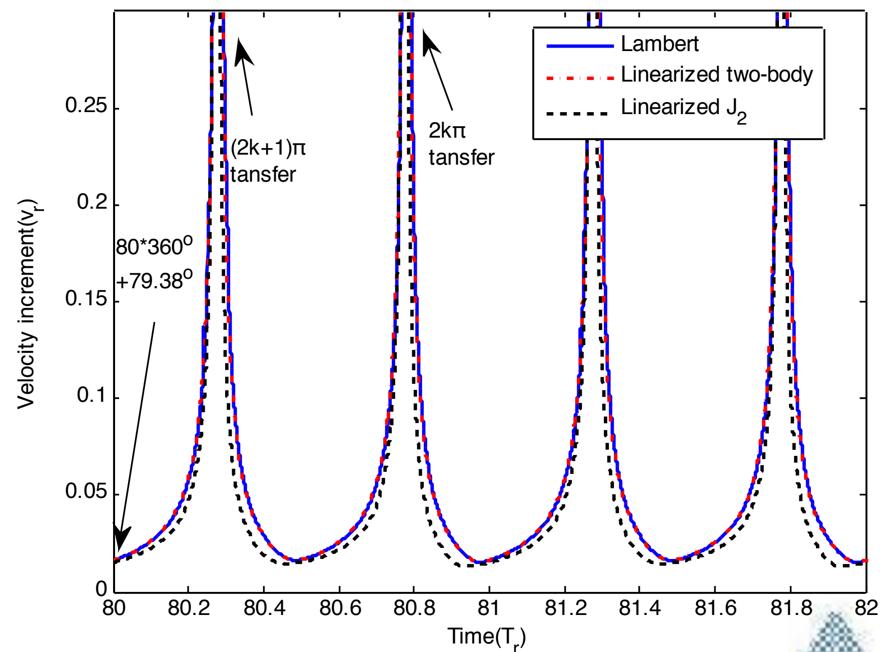


- **Obtain 2000 groups solutions each run, select according to the objective function of both the whole chains and the first chain**

2. Our Approach

◆ Algorithm 2: Mixed-Integer GA for single chain



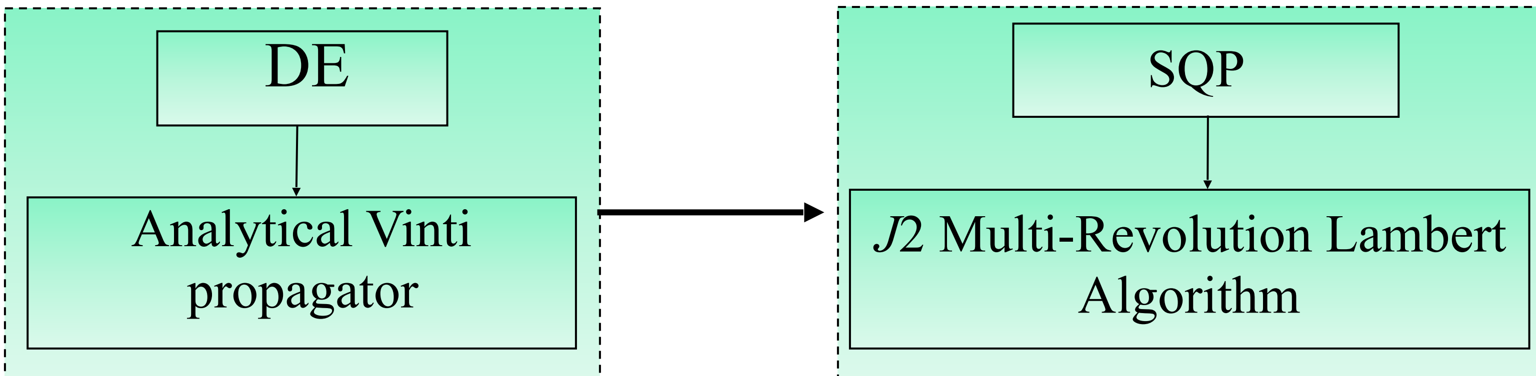


- Sequence and transfer times are both reoptimized by GA
- More accurate model: use **enumeration** to estimate delaV

Zhang et al., J. Guid. Control Dyn., 2014

2. Our Approach

◆ Algorithm 3: rendezvous trajectory optimization



- *J*2 Lambert Algorithm: homotopic techniques to guarantee convergence for long-duration
- DE is parallelized to speed up
- For smaller ΔV , global solution in less than 2 min.
- For larger ΔV , 10-15 min. are required

Yang, Luo, J. Guid. Control Dyn., 2015, 2017

2. Our Approach

◆ Human-guided analysis and adjustment

Single chain

Middle level

Transfer trajectory

Bottom Level

Determine the launch time of the chain based on the regulation of RAAN

Verify the sequence after the optimized chain is obtained

Determine the best body-to-body transfer time based on RAAN

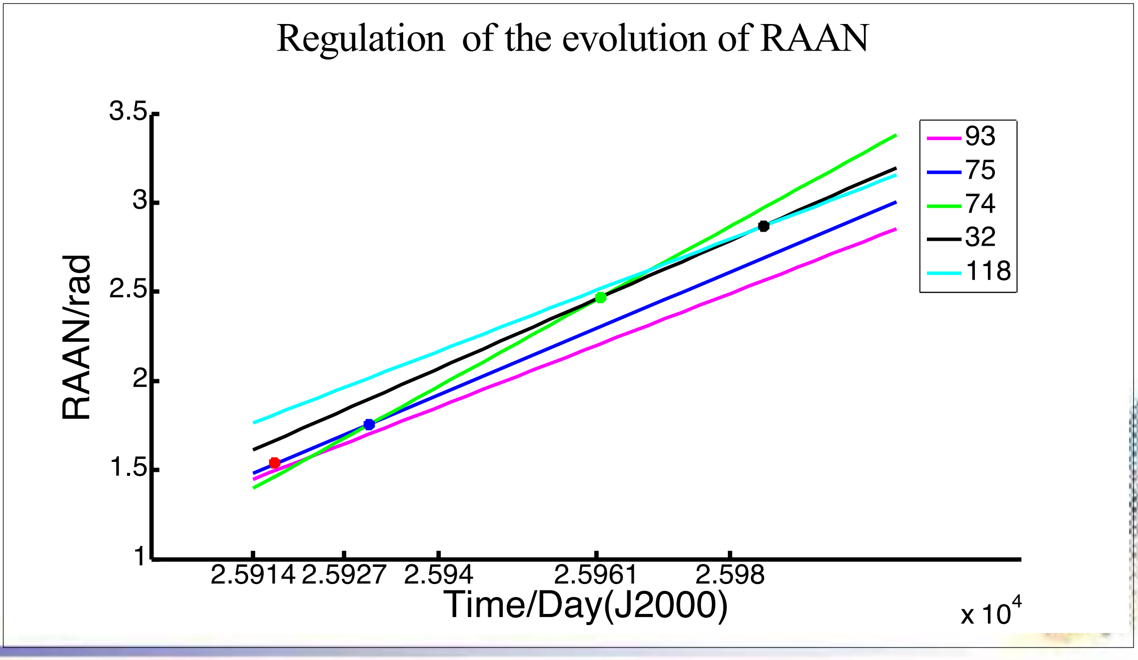
Verify the final optimization results

Mission division

Top level

Analysis for the regulation of RAAN of single mission

Delete the peculiar debris,put it back to the pool and rebunch the left debris



3. Our History and Results

- **Getting a good result quickly but a better one slowly**

Name	Submissions
NUDT Team	14
NPU	13
XSCC-ADL	17
Tsinghua-LAD	13
Jet Propulsion Laboratory	16

Name	Submissions	Last Submission	Best Submission	Debris Removed	Best Score
Jet Propulsion Laboratory	10	May 2, 2017, 5:42 a.m.	May 2, 2017, 5:42 a.m.	123	731.27561037479
NUDT Team	12	May 2, 2017, 3:23 a.m.	May 2, 2017, 3:23 a.m.	123	786.21452662324
XSCC-ADL	12	May 2, 2017, 4:14 a.m.	May 2, 2017, 4:14 a.m.	123	821.379662949282
Tsinghua-LAD	12	May 2, 2017, 3:45 a.m.	May 2, 2017, 3:45 a.m.	123	829.579877503784
NPU	13	April 19, 2017, 4:40 p.m.	April 19, 2017, 4:40 p.m.	123	878.990216662976

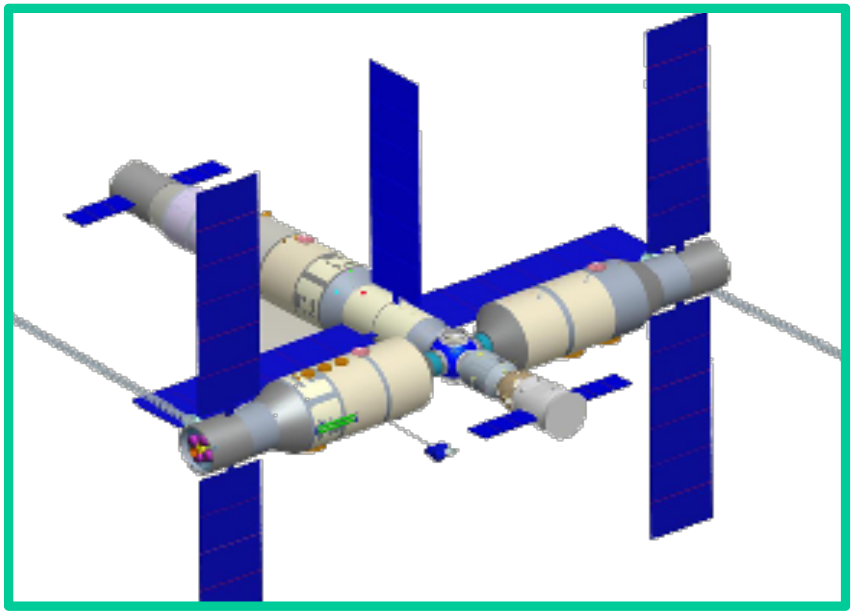
Apr. 19th : 808 （Quickly）

May. 1st : 786 （Slowly）

3. Our History and Results

◆ **Why getting a good result quickly?**

➢ **With effective algorithms and software available**



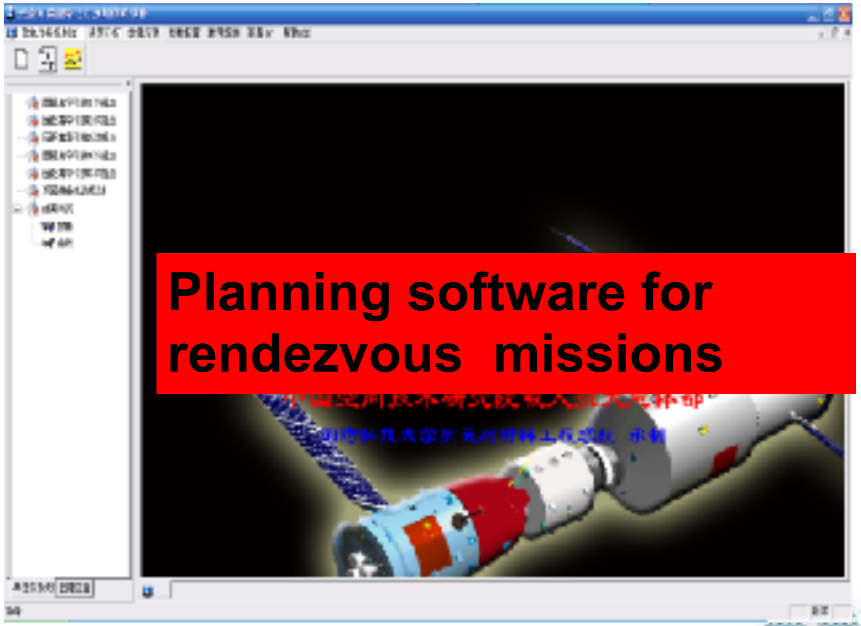
- **Algorithm 1(especially ACO) is modified from the one applied in space station extravehicular missions packing programming**

Zhu, Luo, et al., IEEE CIM, under review

3. Our History and Results

◆ **Why getting a good result quickly**

➢ **With effective algorithms and software available**

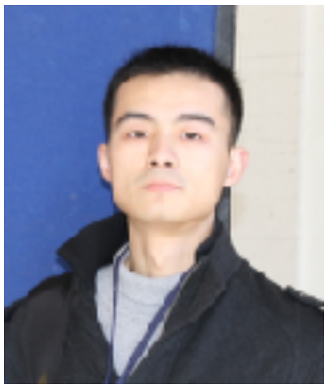


- **Algorithms 2 and 3(especiallly several software in C++) applied in China ShenZhou rendezvous missions since 2011.**

3. Our History and Results

◆ **Why getting a good result quickly?**

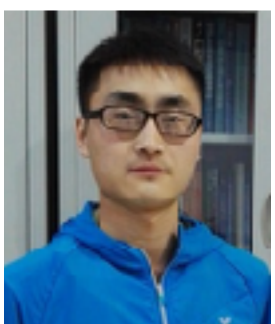
➢ **Young team working with high efficiency**



Zhu Yuehe– Missions division

Luo Yazhong - Coordination

Mou Shuai – Human Analysis


Liang Jun, Sun Zhengjiang – Parallel Computing

Zhang Jin – Single Chain Optimization

Zhu Hai, Yang Zhen – Multi Impulses Optimization

3. Our History and Results

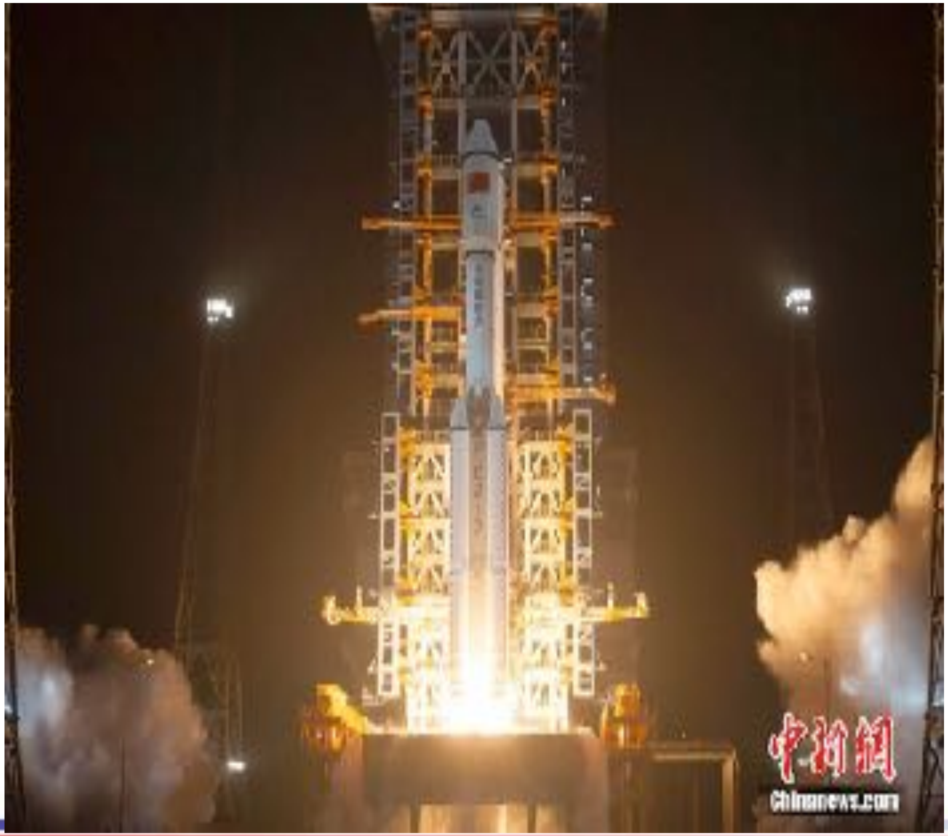
◆ Why getting a good result quickly

- ➢ Chinese Trajectory Optimization Competition (CTOC) since 2009
- ➢ CTOC 8 (2016): Debris remove mission(low-thrust, maximize the total number of debris)

3. Our History and Results

- **Why getting a better result slowly?**

➢ **A one-week break (after April. 19) to support the Tianzhou-I mission**



China first cargo spacecraft launched on April. 19 in Wenchang

3. Our History and Results

◆ **Why getting a better result slowly?**

➢ **Our second time in GTOC**

- **Limited visions : difficulty and complexity in locating GTOC global solutions**

- **We didn't realize the limitations of our approach before April 26**

3. Our History and Results

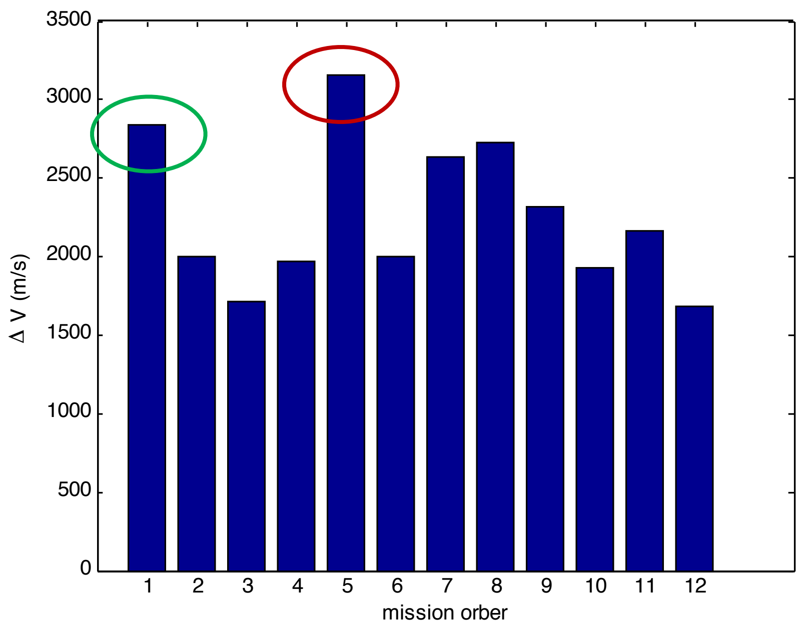
◆ Final result

Mission Order	Start Epoch (MJD)	End Epoch (MJD)	Debris Number	Debris Removal Sequence	Start Mass (kg)
1	23517.00	23811.52	17	0, 115, 12, 67, 19, 48, 122, 7, 63, 61, 82, 107, 41, 11, 45, 85, 47	5478.12
2	23893.80	24092.29	11	58, 28, 90, 51, 72, 69, 10, 66, 73, 64, 52	4106.88
3	24122.30	24427.74	12	84, 86, 103, 16, 121, 92, 49, 23, 20, 54, 27, 36	3809.97
4	24461.50	24660.15	10	8, 43, 9, 55, 95, 14, 102, 39, 113, 110	4081.09
5	24785.00	24975.41	12	83, 75, 22, 35, 119, 24, 108, 37, 112, 104, 32, 114	5782.68
6	25006.00	25198.32	9	118, 65, 74, 50, 94, 21, 97, 79, 120	4024.43
7	25281.60	25454.87	10	62, 1, 40, 76, 89, 99, 15, 59, 98, 116	4877.61
8	25555.40	25669.64	8	117, 91, 93, 70, 18, 105, 88, 46	4909.98
9	25702.40	25860.22	9	5, 53, 33, 68, 71, 80, 57, 60, 106	4419.99
10	25912.74	26055.85	8	2, 81, 96, 6, 100, 30, 34, 26	3902.24
11	26087.53	26262.18	10	87, 29, 101, 31, 38, 25, 4, 77, 13, 3	4267.35
12	26292.26	26381.58	7	44, 111, 56, 78, 17, 109, 42	3584.37

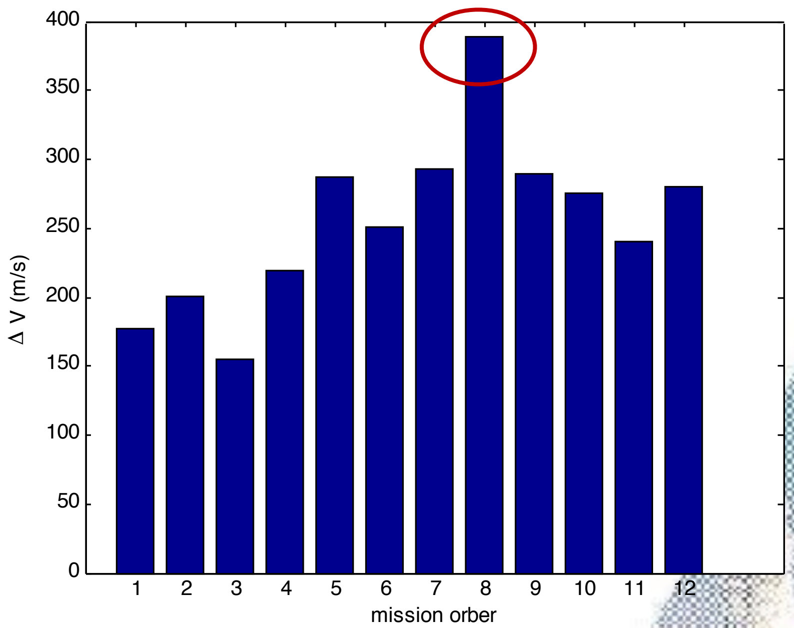
3. Our History and Results

◆ Final result

- Most total ΔV are between 1500 m/s and 2500 m/s
- Mission 5 is not so good, high total ΔV(12 debris)
- Mission 8 is not yet good, high average ΔV(8 debris)
- Mission 1 is acceptable (17 debris)



Total ΔV of each mission

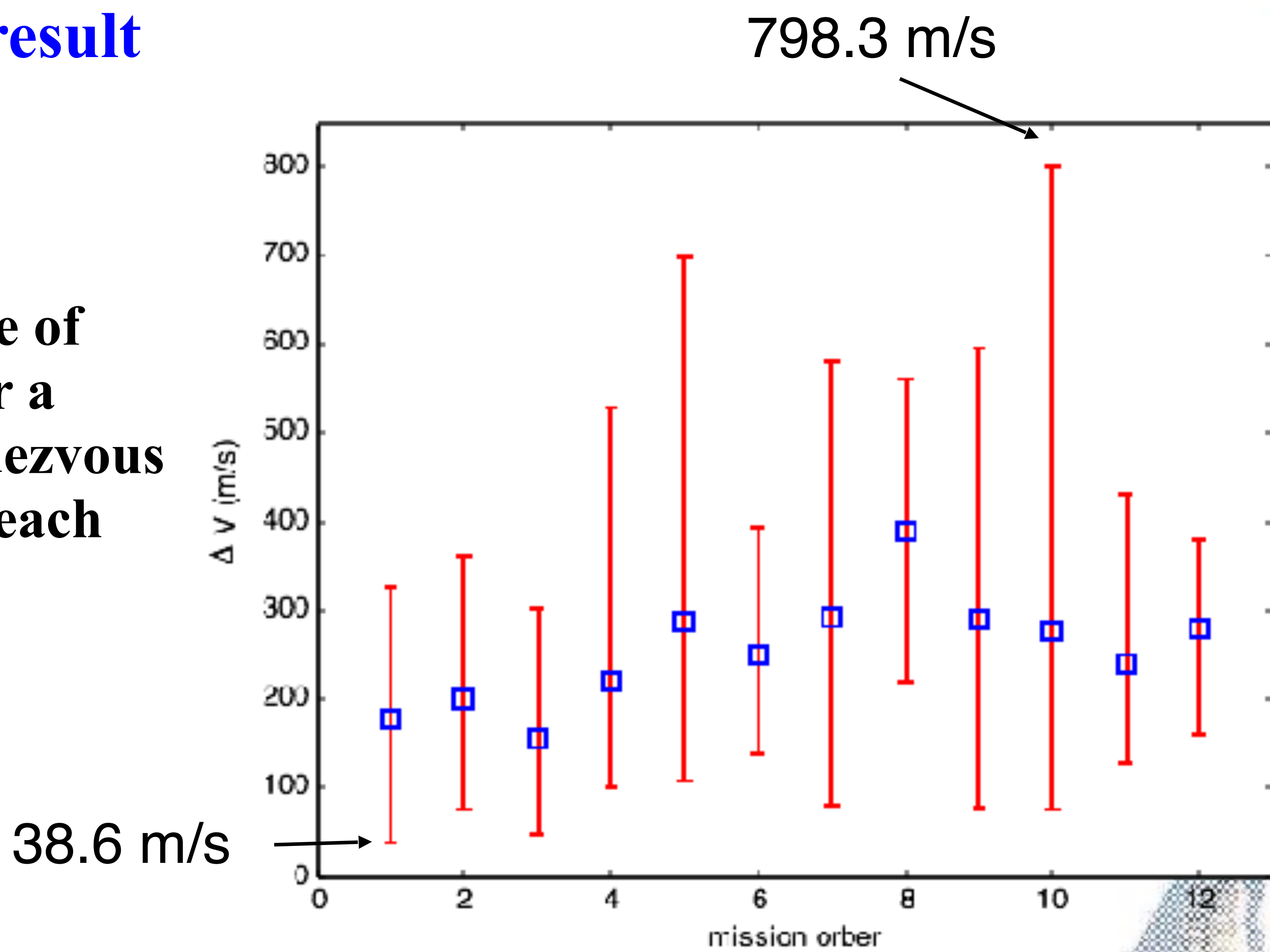


Average ΔV of each mission

3. Our History and Results

- **Final result**

Wide range of the ΔV for a single rendezvous process of each mission



Minimum and maximum ΔV of each mission

4. Discussions

◆ Evaluation of our optimization tools

➢ **Based on the sequence of JPL's solution, we made some tests for our debris-to-debris transfer optimization tools.**

Mission	ΔV, *m/s*
1	161.8,139.2,65.8,208.2,115.2,300.1,564.9,78.3,105.0,233.3,453.5,340.4
2	659.0,301.1,252.1,143.8,146.8,68.6,40.6,84.2,105.3,448.5,148.0

Our results: 682 252 148 85 450

- **It seems our debris-to-debris transfer optimization tools are not so worse than JPL.**

4. Discussions

- **Issues in our optimization approach**

Why cannot get better solution?

- **Due to the limitation of our ACO, we had to determine the chains one by one. Only the local optimal solution could be obtained.**

- **The estimation of optimal ΔV and [illegible] are not accurate enough (especially when ΔV> 500 m/s and [illegible] >25 day, the deviation could be up to 30%).**

- **We are now working on these issues (less than 720 is promising)**

4. Discussions

◆ **Further work**

- **Super computer: NUDT's Tianhe-II in solving such large-scale optimization problem**

- **Orbit design using machine learning: estimation model base on neural network, stochastic search(ACO, GA, DE) using knowledge-guided strategy, etc.**

Thank you for your attention !

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