GTOC9 Results and Methods of Team 2 – Tsinghua University

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Analyzing the Cost Function

$$J=\sum_{i=1}^{n}\left[c_i+\alpha\left(m_{0i}-m_{dry}\right)^2\right],c_i=c_m+\frac{t_{submission}-t_{start}}{t_{end}-t_{start}}\left(c_M-c_m\right)$$

$$m_{0i}=\left(\left(\left(m_{dry}+m_{de}\right)e^{\frac{\Delta v}{I_{sp}g_0}}+m_{de}\right)e^{\frac{\Delta v}{I_{sp}g_0}}\boxed{?}\right)e^{\frac{\Delta v}{I_{sp}g_0}}=m_{dry}e^{\frac{(N_i-1)\Delta v}{I_{sp}g_0}}+m_{de}\frac{e^{\frac{N_i\Delta v}{I_{sp}g_0}}-1}{e^{\frac{\Delta v}{I_{sp}g_0}}-1}$$

$$m_{dry}e^{\frac{(N_i-1)\Delta v}{I_{sp}g_0}}\Rightarrow s_0^{c_i},S=s_0^{c_1}+s_0^{c_2}+\boxed{?}+s_0^{c_n},c_1+c_2+\boxed{?}c_n=\text{const}\Rightarrow S_{\min}\ \text{when}\ c_1=c_2=\ldots=c_n$$

- ➢ Run with time!
- ➢ Ensure the transfer ΔV is not too large.
- ➢ Average the number of debris in each mission.
- ➢ Make the number of missions as small as possible.

Estimation method of transfer ΔV

- Quasi-circular orbit
- Many-revolution transfer

$$\Delta V_a = \frac{1}{2}\frac{\Delta a}{a_0} V_0$$

$$\Delta V_e = \frac{1}{2}\Delta e V_0$$

$$\Delta V_i = \Delta i V_0$$

$$\Delta V_\Omega = \sin i_0 \Delta\Omega V_0$$

$$\Delta V = \sqrt{\Delta V_a^2 + \Delta V_e^2 + \Delta V_i^2} + \left|\Delta V_\Omega\right|$$

Edelbaum T N. Propulsion requirements for controllable satellites[J]. ARS Journal, 1961, 31(8): 1079-1089.

Estimation method of transfer time

Transfer time interval: $[t_{low}, t_{upp}]$,

For example, $t_{low} = 1$ day and $t_{upp} = 25$ days.

t_s is the start epoch,

t_{match} is the epoch when the RAAN of two debris is exactly the same after t_s

If $t_{match} - t_s \in [t_{low}, t_{upp}]$,

$t_{transfer} = t_{match} - t_s$

calculate $\Delta V_{transfer}$

Else calculate ΔV_{low} and ΔV_{upp}

If $\Delta V_{low} < \Delta V_{upp}$

$t_{transfer} = t_{low} - t_s$

$\Delta V_{transfer} = \Delta V_{low}$

Else

$t_{transfer} = t_{upp} - t_s$

$\Delta V_{transfer} = \Delta V_{upp}$

If $\Delta V_{transfer} < \Delta V_{max}$

feasible

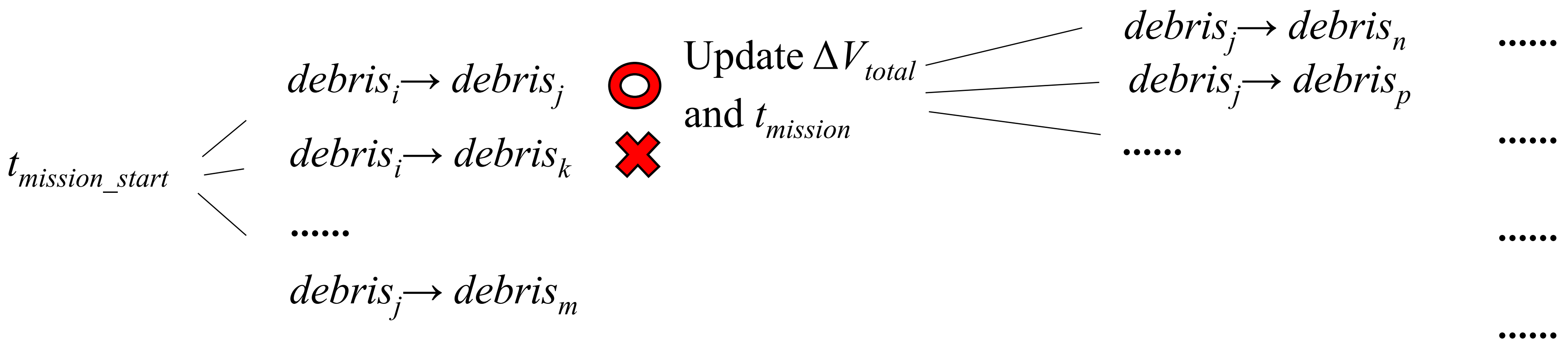
Else

infeasible

Search Strategy

First Week:

In one mission: $t_{mission\_start} = [t_0,\ t_0 + \Delta t,\ t_0 + 2\Delta t,\ \ldots, t_f]$, Δt is the discrete time interval



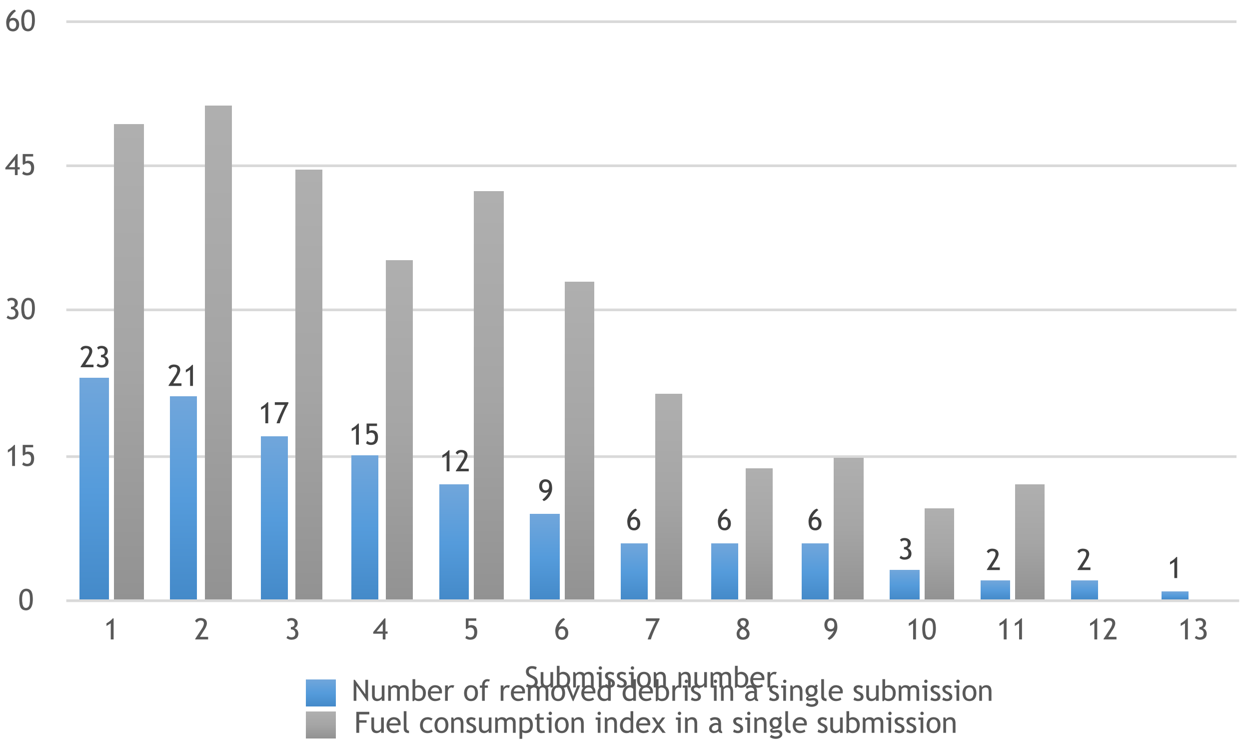
- ➢ Pruning is used.
- ➢ Stop condition: $\Delta V_{total} > \Delta V_{total\_max}$ or no more debris can be selected
- ➢ Sequence with most debris and least ΔV_{total} will be selected as this mission's sequence

Search Strategy

Result of First Week

Submission number: 13

Performance index: 1000



Work of Next Two Weeks

Objective： Try to avoid local optimal solutions and average the number of debris in each mission.

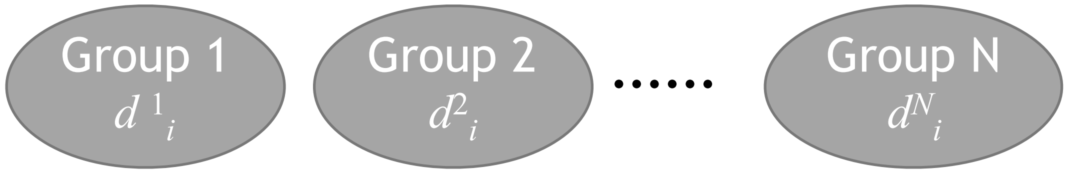
Search Strategy

Improvements of Last 4 Days:

Group debris randomly：

➢ Before each mission starts, the rest debris will be randomly and evenly divided into each group.

➢ In one mission, the number of removed debris in the same group can not be more than an upper limit.



Assume the upper limit is 3, then $d^1_1 \rightarrow d^1_2 \rightarrow \ldots\ldots \rightarrow d^1_3 \rightarrow d^1_4$ ✖

Simplify Sequence：

➢ If the last debris and the last arrival time are the same, then these two sequences will be taken as one sequence.

$$\begin{array}{l} \{(id_1,t_1),(id_2,t_2),(id_3,t_3),(id_4,t_4),(id_5,t_5)\} \\ \{(id_1,t_1'),(id_4,t_2'),(id_2,t_3'),(id_3,t_4'),(id_5,t_5)\} \Rightarrow \{(id_1,id_2,id_3,id_4,id_5),(id_5,t_5)\} \\ \{(id_2,t_1''),(id_1,t_2''),(id_4,t_3''),(id_3,t_4''),(id_5,t_5)\} \end{array}$$

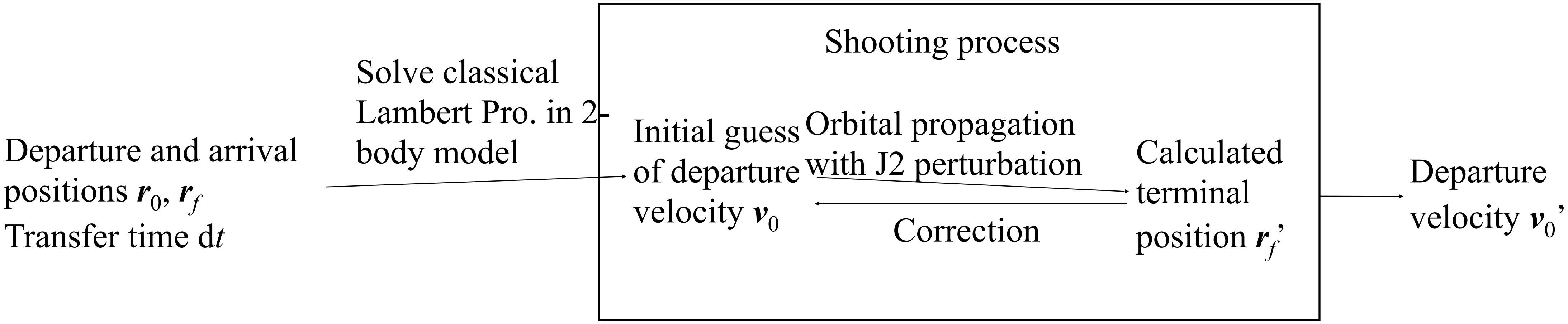
Use Particle Swarm Optimization to optimize the arrival time：

➢ The objective function is ΔV_{total}.

Contents

1. Solve Lambert problem with J2 perturbation

Orbital propagation
- 1. Position & velocity ↔ Instantaneous orbit elements ↔ Mean orbit elements
- 2. Numerical integration



If the shooting process doesn't converge, increase the magnitude of J2 from 0 gradually (homotopic approach).

2. Multiple impulse optimization

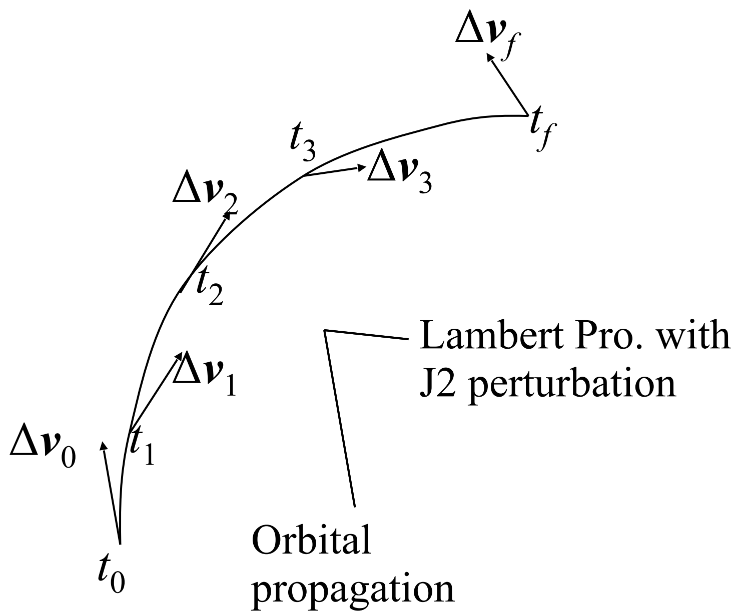
Sequence: T_1 T_2 … T_i T_{i+1} … $T_{N\text{-}1}$ T_N

debris 1, debris 2, debris i, debris i+1, debris N-1, debris N

Departure time: $T_i + 5\text{day} \leq t_0 < T_{i+1}$ t_0 free

Arrival time: $t_f = T_{i+1}$ t_f fixed

Case	Optimization variables
Double-impulse	t_0
Multiple-impulse	t_0 t_1 t_2 … t_n $\Delta\boldsymbol{v}_0$ $\Delta\boldsymbol{v}_1$ $\Delta\boldsymbol{v}_2$ … $\Delta\boldsymbol{v}_{n\text{-}1}$ (n=1,2,3)



2. Multiple impulse optimization

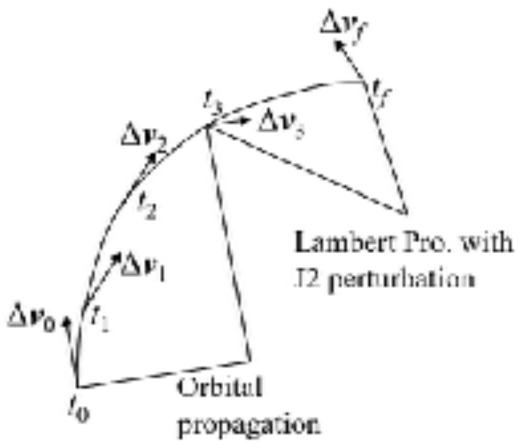
Parallel computing

PSO algorithm

(Orbital propagation 1 is used)

2-impulse transfer	3-impulse transfer	4-impulse transfer	5-impulse transfer

Choose the case where the total Δv is minimum



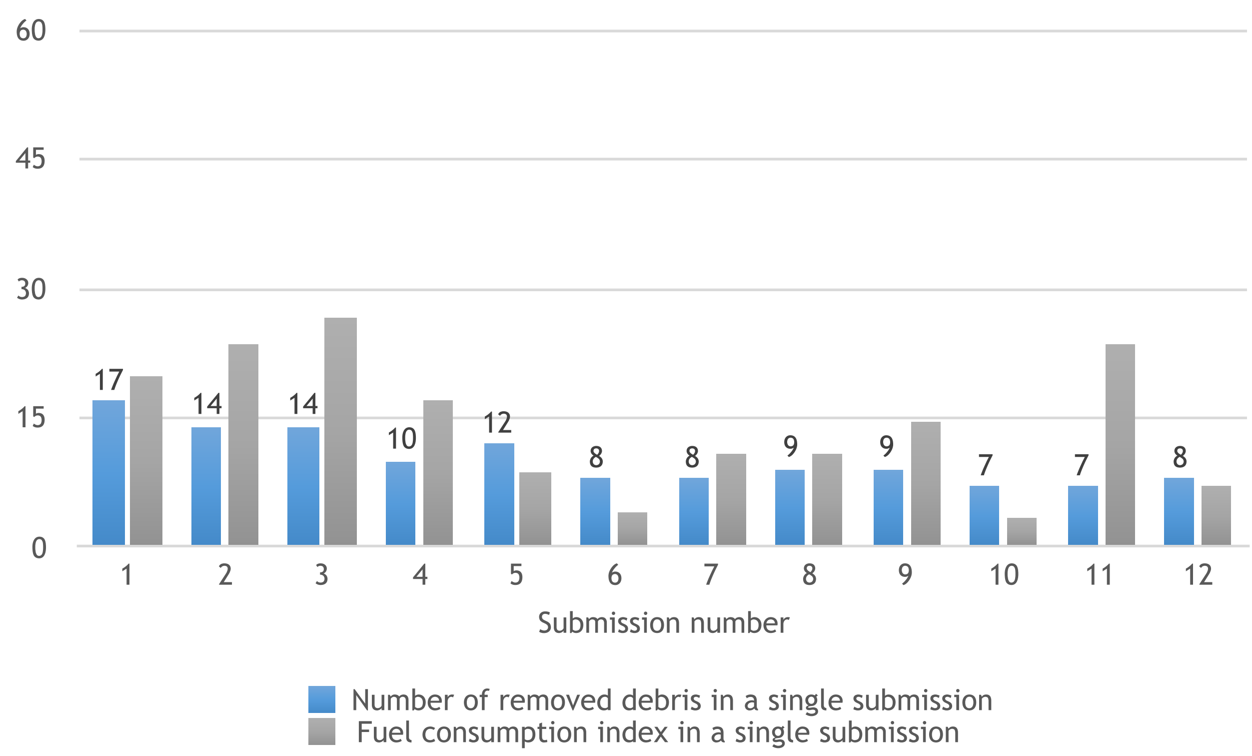
Based on the results of t_0, t_1, t_2,...t_n, $\Delta \boldsymbol{v}_0$, $\Delta \boldsymbol{v}_1$, $\Delta \boldsymbol{v}_2$, ... $\Delta \boldsymbol{v}_{n\text{-}1}$, solve the accurate trajectory using orbital propagation 2 (numerical integration).

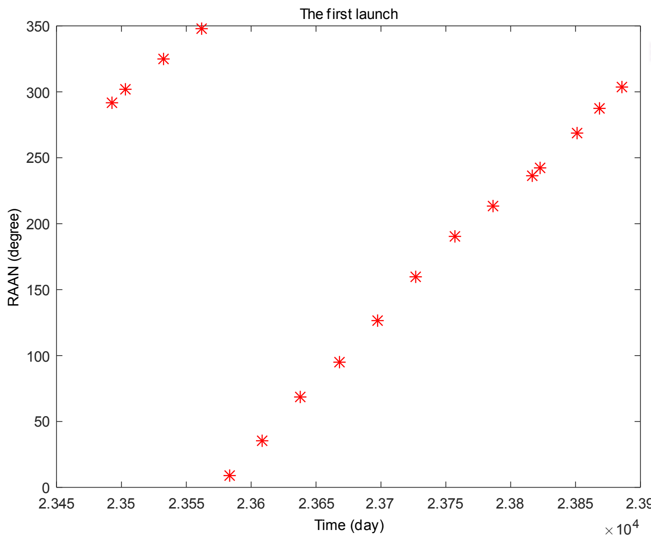
Contents

Results

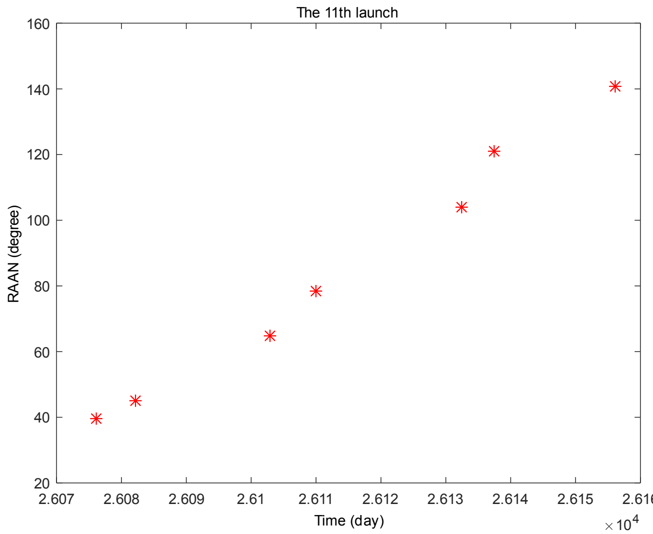
Final results (May 2, 2017, 3:45 a.m.)

Submission number: 12 Performance index: 829.58





RAAN in submission 1
(fuel consumption: 2647.93kg)



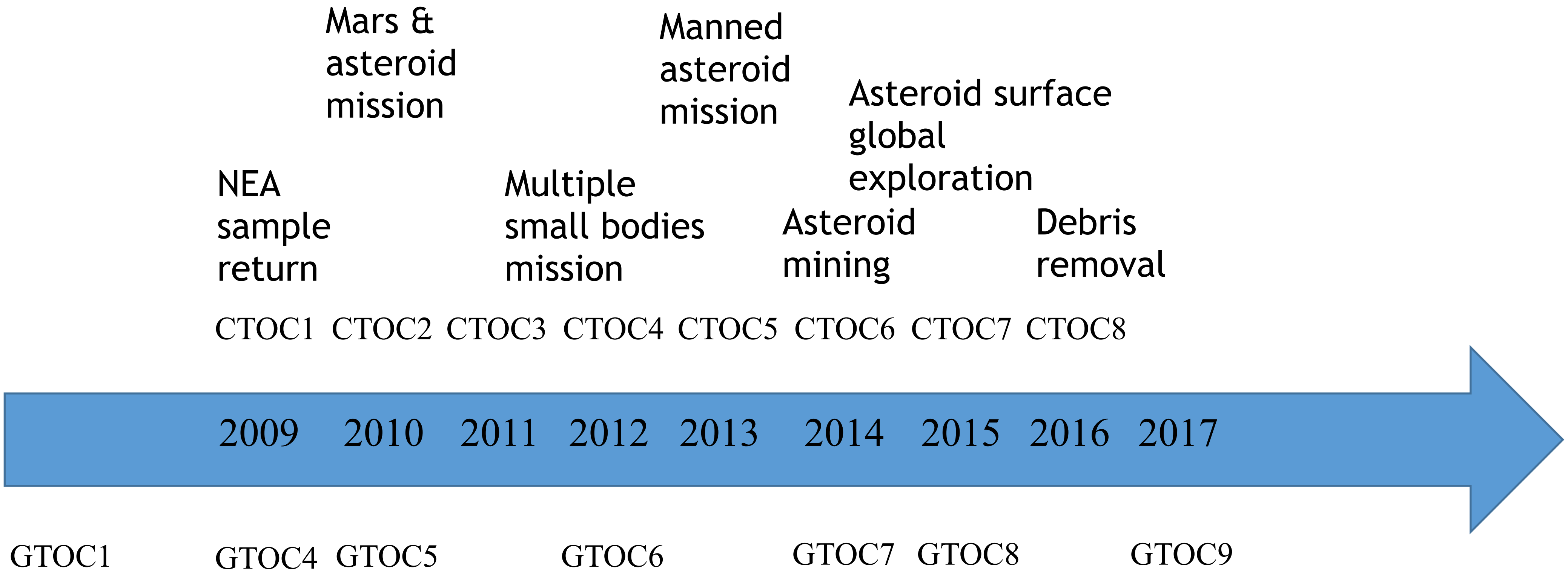
RAAN in submission 11
(fuel consumption: 3212.19kg)

Conclusions

1. More work needs to be done in global optimization algorithms
2. The calculation speed and stability of PSO need to be improved
3. Large-scale computing is a significant technique in global search
4. Glad to learn from domestic and abroad scholars

Brief Introduction to CTOC

- ➢ Chinese Trajectory Optimization Competition - CTOC
- ➢ Inaugurated by **Tsinghua University** in 2009
- ➢ **Winners:** Tsinghua, CAS, NUDT, XSCC, BIT&CASIC



Thanks very much for your attention!

Question?