О международных соревнованиях по глобальной оптимизации траекторий

GTOC — Global Trajectory Optimization Competitions

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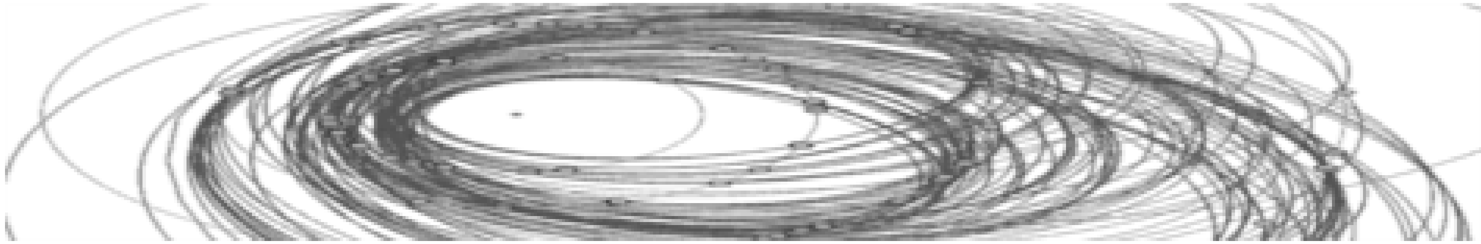
The Global Trajectory Optimization Competition — это соревнования, проводимые раз в два года в течение примерно одного месяца, во время которого лучшие аэрокосмические инженеры и математики всего мира пытаются решить "почти невозможную" задачу по проектированию межпланетных траекторий.

Условия задачи очередных соревнований определяет команда-победитель предыдущего выпуска, которая также вольна полностью определять правила соревнований.

Проблема должна быть связана с проектированием межпланетных траекторий, а ее сложность должна быть достаточно высокой, чтобы обеспечить явного победителя конкурса. За прошедшие годы различные постановки задач и полученные решения дали внушительный вклад в теорию и методологию решения таких сложных задач для научного сообщества.

Соревнования GTOC открыты для всех желающих, чтобы принять участие в очередном издании, посетите https://sophia.estec.esa.int/gtoc_portal/

HIC FUTURA PARANTUR
ESA ADVANCED CONCEPTS TEAM

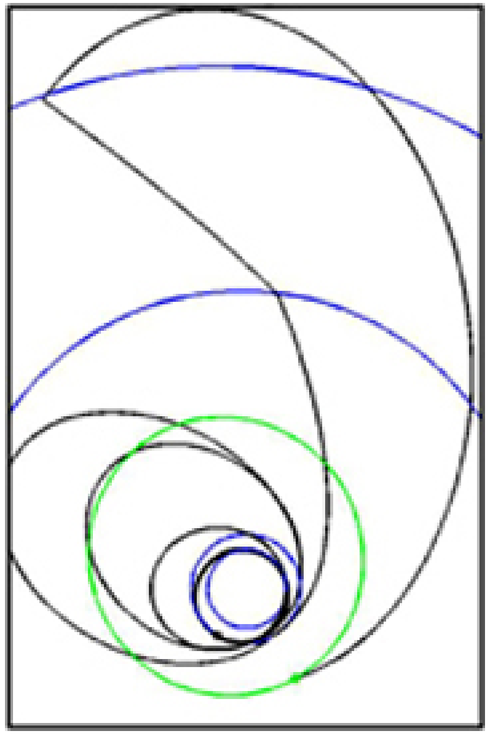


esa

GTOC 1 – cup of rocket science “Save the Earth”

The main objective of the optimisation is to maximise the change in the semi-major axis of the asteroid 2001 TW229 subsequent to the **impact of** an electric propelled **spacecraft:** $J = m_f \left| \vec{U}_{rel} \cdot \vec{v}_{ast} \right|$.
Attraction of the **Sun**, **Mercury, Venus, the Earth, Mars**, **Jupiter** and **Saturn** is considered.

Launch from 2010 to 2030, maximum time of flight is 30 years



Rank 1: JPL (USA)

The trajectory makes use of a planetary sequence EVEEEJSJA. *Only the first phase (Earth Venus) is propelled*. The overall fuel consumption is of roughly 60kg. The team uses a *shape method* based on exponential sinusoids to ensure a global search of the solution space. A local optimisation was then used to refine the trajectory based on a NLP solver that is fed with analytical gradients by *considering the thrust as a sequence of discrete impulses*. The accuracy of this model is high and has been independently verified by forward in time integration.

The complexity of a global optimisation problem is closely related to:
- The size of the basin of attraction of the global optimum
- The presence of embedded or isolated global minima
- The number of local minima

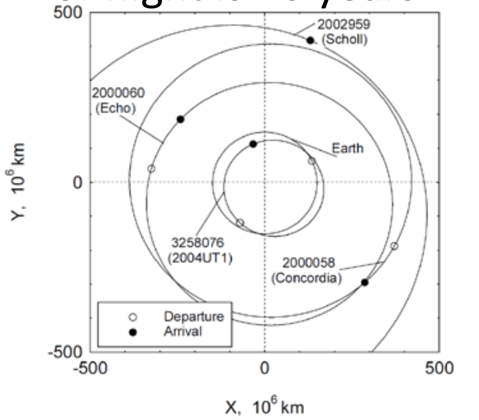
Rank	Team name	Flyby sequence	Value
1	JPL	EVEEEJSJA	1,850,000
2	Deimos Space	EVVEEVVEVEJSJA	1,820,000
3	GMV	EEVEEJSA	1,455,000
4	MAI & Krunishev	EVEVEEA	1,364,000
5	Politecnico di Torino	EVVJA	1,290,000
6	CNES/CS	EEVEEJSJA	1,194,000
7	Glasgow University	EEVVA	385,000
8	Moscow University	EA	351,152
9	Alcatel	EA	330,385
10	DLR	EA	330,000
11	Tsinghua University	EA	89,000

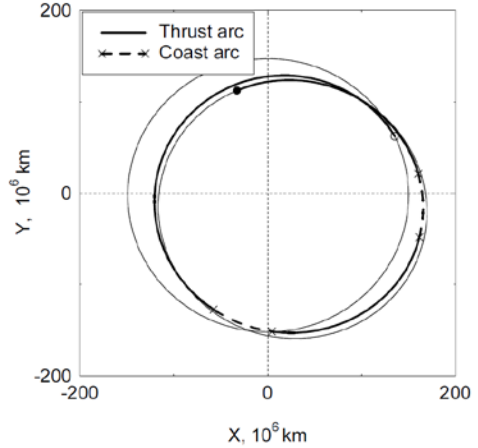
7th November 2005

GTOC 2 – "Multiple Asteroid Randezvous"

A trajectory must be designed for a low-thrust spacecraft which launches from Earth and subsequently performs a rendezvous with one asteroid from each of four defined groups of asteroids (extremely large number of combinations: 41 billions). A stay time of at least 90 days is required. *Gravity-assists are not permitted*. $J = m_f / t_f$.

Launch from 2015 to 2035, maximum time of flight is 20 years





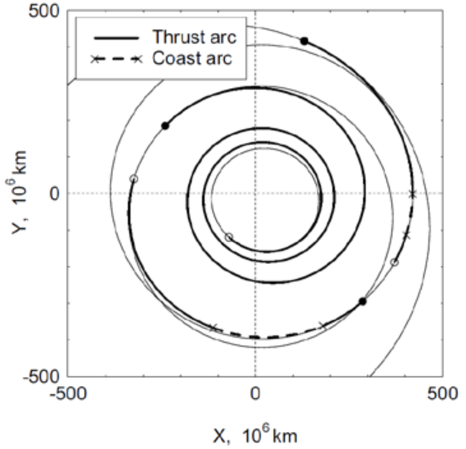
The criteria for selecting a problem this year are similar to those used in the first competition:

- Global optimisation over a large design space (e.g. large launch window), with many local optima.
- Unusual objective function or constraints — no canned methods or existing software can likely fully solve the problem.
- Problem is easy enough to tackle in a 3-4 week timeframe for experienced mission designers or mathematicians, including exploration of new algorithms.
- Problem solutions can be easily verified.

Rank 1: Politecnico di Torine (Italy)

The patched-conic approximation. The four asteroids roughly lie on the same plane.

The desire of a monotone increase of the spacecraft energy suggests the group sequence. Phasing.



Ranking of Returned Solutions

Rank	Team		J (kg/yr)
1	4:	Politecnico di Torino	98.64
2	13:	Moscow Aviation Institute, and Khrunichev State Research and Production Space Center	87.93
3	10:	Advanced Concepts Team, ESA	87.05
4	15:	Centre National d'Etudes Spatiales (CNES)	85.43
5	1:	GMV Aerospace and Defence	85.28
6	2:	German Aerospace Center (DLR)	84.48
7	9:	Politecnico di Milano	82.48
8	19:	Alcatel Alenia Space	76.37
9	14:	Moscow State University	75.08
10	7:	Tsinghua University	56.87
11	18:	Carnegie Mellon University, J.J. Arrieta-Camacho	27.94
–	17:	University of Glasgow, *et al.*	73.87[a]
–	21:	Technical University of Delft and Dutch Space	15.95[b]
–	23:	Facultes Universitaires Notre-Dame de la Paix (FUNDP)	–[c]
–	26:	University of Maribor, Bostjan Eferl	–[d]

[a] Significant position and velocity violations at the asteroids and Earth
[b] Significant position and velocity violations at the asteroids and Earth, and flight time limit violation
[c] Only one leg computed (Earth to Group 4)
[d] Only a proposed method described, no solution computed

GTOC 3 – "Multiple Sample Return"

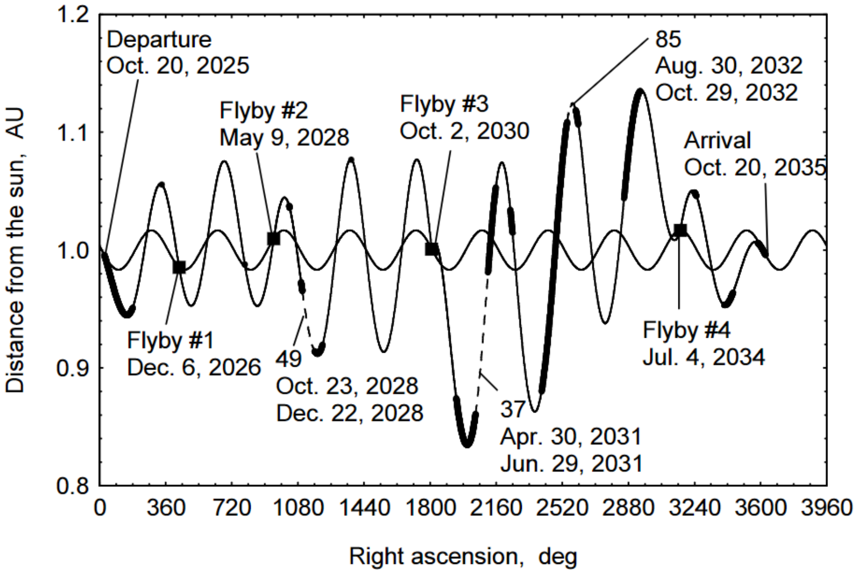
An asteroid sample return mission had to be designed to 3 out of 140 asteroids. Earth fly-bys were allowed. The objective function was the ratio between the final spacecraft mass and the total mission time plus a term rewarding longer stay times on the asteroids to increase the science return.

$$J = \frac{m_f}{m_i} + K \frac{\min_{j=1,3}(\tau_j)}{\tau_{max}}$$

Launch from 2016 to 2025, maximum time of flight is 10 years

Rank 1: CNES (France)

The team used two different local optimisation methods. The first one is a non linear simplex method. It was used to solve the nonlinear programming problem that optimizes Earth-to-asteroid, asteroid-to-asteroid and asteroid-to-Earth bi-impulsive (impulses at departure and arrival) transfers with or without intermediate Earth flyby (departure, flyby and arrival dates are determined for minimum ΔV). Simple legs were joined together to build mission scenarios and a global search among the listed asteroids provided the most promising asteroid sequences. An indirect shooting method based on Pontryagin's Maximum Principle was then used to compute the related low-thrust trajectories while determining the stay-times at each asteroid to maximize J



Team 4 solution (thick line = thrust arcs, thin line = coast arcs).

Rank	Team	Index J	Sequence	Departure Arrival, MJD	Final mass m_f, kg	Min. stay τ_{min}, days
1	4 CNES	0.8700	E E E 49 E 37 85 E E	60968 64620	1733	60
2	14 JPL	0.8685	E E 49 E 37 85 E E	60945 64597	1730	60
3	2 Georgia Tech	0.8638	E 49 E 37 85 E E	60996 64648	1721	60
4	17 Deimos	0.8617	E 49 E E 37 85 E E	60964 64616	1717	60
5	18 TAC	0.8372	E 88 E 96 49 E	57726 61316	1647	245
6	13 TAS	0.8353	E 96 E 88 49 E	58169 61799	1647	211
7	8 MAI	0.8321	E 88 E 96 E 49 E	58075 61654	1658	60
8	1 GMV	0.8279	E E 96 76 E 49 E	59259 62870	1649	60
9	5 MSU	0.8257	E 96 E 88 49 E	58478 61998	1633	165
10	7 Glasgow	0.8063[a]	E 88 19 49 E	58813 62365	1606	62
11	9 Tsinghua	0.7946	E 88 76 49 E	58091 61642	1565	225
12	11 Pisa	0.7744	E 88 49 19 E	58094 61319	1528	191
13	25 IKI	0.7537[b]	E 76 96 49 E	58129 62332	1501	60
-	21 Milano	0.8376[c]	E 88 E 96 49 E	58169 61693	1663	110
-	6 ESA	0.8172[c]	E 96 88 49 E	58144 61650	1614	187
-	10 Delft	-[d]	E 96 122 85 E	59308 62416	1130	94

[a] minor constraint violation on Earth's position at departure and rendezvous, deemed to have a negligible influence on the results
[b] minor constraint violation on time of flight, deemed to have a negligible influence on the results
[c] late solution, due to misunderstanding of problem data
[d] major constraint violations

12th November 2007

GTOC 4 – “Asteroids billiard”

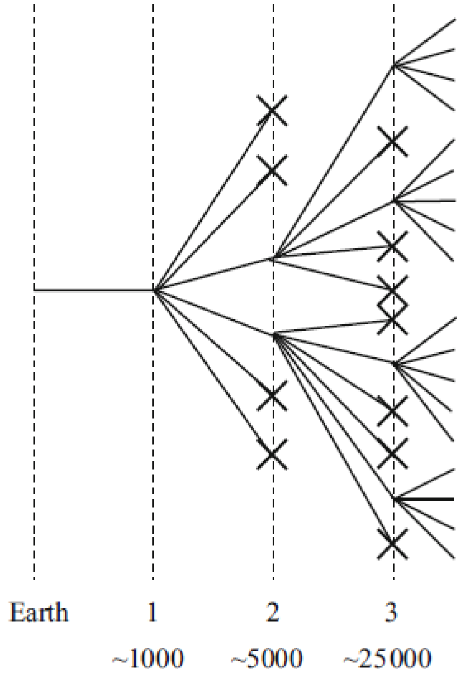
A spacecraft has to visit as many Near Earth Asteroids as possible by performing fast consecutive fly-bys to finally randezvous with a NEA. The objective function is the **number of asteroid visited**. Secondary performance indices, to break ties, are the **final spacecraft mass** and total time of flight.

Launch from 2015 to 2025, maximum time of flight is 10 years, 1436 asteroids

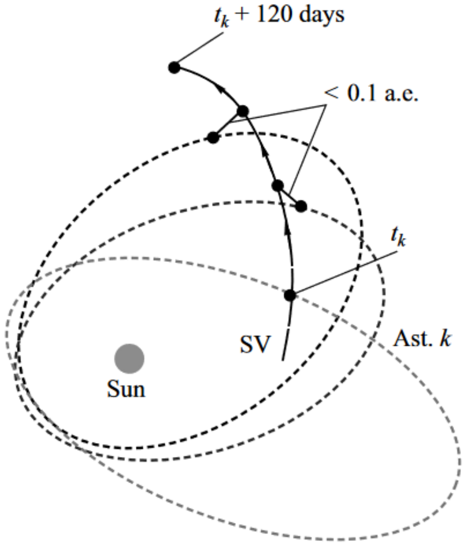
Gravity-assists are not permitted.

Rank 1: Moscow State University (Russia)

CHOOSING PROMISING SEQUENCES OF ASTEROIDS



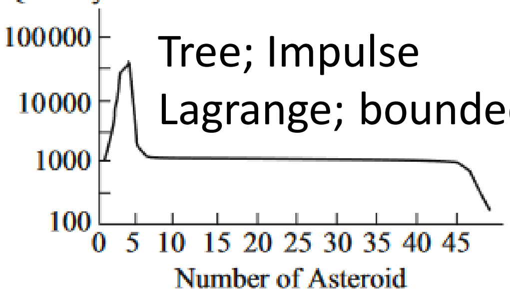
Flight bush.



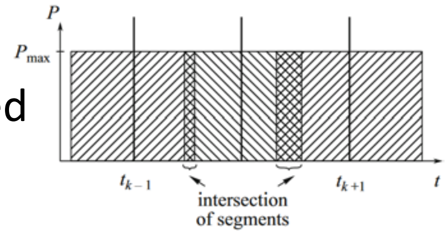
Adding a level: searching for suitable asteroids.

Scientists would not agree, before this edition of GTOC, on how many asteroids could be encountered during a low-thrust interplanetary mission. The number 44 (in 10 years) appeared to scientific community as a positive surprise.

Quantity of branches



Tree; Impulse Lagrange; bounded



rank	team #	team name	J	$K = m_f$ [kg]	duration [year]	rendezvous asteroid
1	15	Moscow State University	**44**	**553.46**	10	2000SZ162
2	25	The Aerospace Corporation	**44**	**516.83**	10	2000SZ162
3	12	Advanced Concepts Team, ESA	**42**	**511.45**	10	2008UA202
4	20	DEIMOS Space	**39**	**605.44**	10	2006BZ147
5	41	GMV	**39**	**516.30**	10	2007YF
6	19	Jet Propulsion Laboratory	**38**	**515.87**	10	138911
7	8	Politecnico di Torino, Universita di Roma La Sapienza	**36**	**574.44**	10	2006QQ56
8	32	University of Texas at Austin, Odyssey Space Research , ERC Incorporated	**32**	**639.86**	9.69	2006UB17
9	34	University of Glasgow University of Strathclyde	**29**	**715.21**	9.98	2006QQ56
10	13	Thales Alenia Space	**27**	**533.25**	10	2006QQ56
11	10	University of Trento	**26**	**721.73**	9.73	2006UB17
12	46	University of Bremen, Politecnico di Milano	**26**	**577.97**	9.82	2008GM2
13	31	Moscow Aviation Institute, Research Institute of Applied Mechanics and Electrodynamics	**24**	**720.62**	10	2007YF
14	2	Georgia Institute of Technology	**24**	**500.27**	9.5	2008UA202
15	42	TOMLAB	**22**	**615.22**	9.65	2006XP4
16	6	VEGA	**20**	**653.07**	10	2008UA202
17	5	DLR German Space Operations Center Aachen University of Applied Sciences	**20**	**635.09**	10	2005BG28
18[a]	38	Team Astroshape	**20**	**524.48**	10	2006SV5
19	40	DLR Institute of Space Systems	**19**	**592.35**	10	138911
20	4	Tsinghua University	**18**	**539.98**	10	138911
21	11	University of Missouri	**15**	**836.06**	10	2005CD69
22	9	Beijing University of Aeronautics and Astronautics	**13**	**651.87**	9.98	2006RJ1
23[a]	35	Texas A&M University	**12**	**697.93**	10	2006UB17
_[b]	37	Nanjing University of Aeronautics and Astronautics	**54**	**836.53**	9.58	2005SN5
_[b]	23	CHOPIN Team	**25**	**1436.33**	10.12	2008UA202
_[c]	18	Chinese Academy of Sciences	**19**	**872.65**	9.68	2004XG

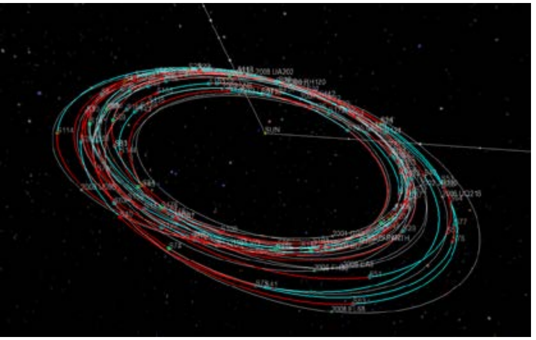
[a] minor constraints violation having negligible influence on the results
[b] major constraints violation, solution not ranked
[c] late solution

2nd March 2009

GTOC 5 – "Penetrators"

Some small penetrators are to be delivered to as many asteroids as possible via a close fly-by. The asteroids first have to be visited (randezvous) and a main payload delivered, only then the penetrator can be deployed in a successive fly-by with a velocity not less than ΔV_{min}= 0.4 km/s. The objective function rewards visits and penetrators deployed, as well as extra points for the asteroid Beletskij. Index J equal to the number of spacecraft mission is maximized. An asteroid rendezvous and delivery of the scientific block is estimated by 0.2, and subsequent penetration by 0.8. Secondary performance are the final spacecraft mass and total time of flight.

Launch from 2015 to 2025, maximum time of flight is 15 years, 7075 asteroids



4th October 2010

Rank 1: JPL (USA)

Led by Anastassios Petropoulos, the team from Jet Propulsion Laboratory (JPL) won this edition with a trajectory designed entirely using low-thrust models (i.e. no chemical propulsion model was employed preliminarily)

Rank	Team	Team name	J	T, day
1	29	Jet Propulsion Laboratory (USA)	18	5459.29
2	13	Politecnico di Torino, Universita' di Roma (Italy)	17	5201.58
3	20	Tsinghua University, Beijing (China)	17	5277.86
4	5	ESA-ACT and Global Optimization Laboratory	16	5181.81
5	14	Georgia Institute of Technology (USA)	16	5420.16
6	1	The University of Texas at Austin, Odyssey Space Research, ERC Incorporated (USA)	15	5394.16
7	2	DLR, Institute of Space Systems (Germany)	14	5438.00
8	35	Analytical Mechanics Associates, Inc. (USA)	13	5144.64
9	18	Aerospace Corporation (USA)	12.2	5472.08
10	4	VEGA Deutschland (Germany)	12	4873.99
11	16	University of Strathclyde, University of Glasgow (Scotland)	12	5241.90
12	21	"Mathematical Optimization" at Friedrich-Schiller-University, Jena (Germany)	11	5475.55
13	26	College of Aerospace and Material Engineering, National University Of Defense Technology (China)	8	4819.10
14	33	University of Missouri-Columbia (USA)	1.8	4705.33
15	23	InTrance - DLR / FH Aachen / EADS (Germany)	1.2	1271.0
		Late solution		
	3	University of Trento (Italy)	10	5241.82
	17	College of Aerospace and Material Engineering, National University of Defense Technology (China)	13	5343.31
		Major constraints violation, solution not ranked		
	28	AEVO-UPC (Germany/Spain)	6.4	5290.0
	30	Michigan Technological University, The University of Alabama (USA)	4.2	4215.45

GTOC 6 – “Global mapping of Galilean moons”

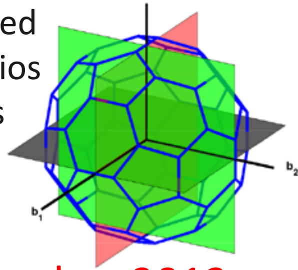
The four Galilean moons of Jupiter (Io, Europa, Ganymede and Callisto) have to be mapped globally using repeated multiple fly-bys of a low-thrust spacecraft. Each fly-by pericenter vector defines the visited point on the moon surface that is considered as divided into 32 faces in a similar manner as soccer balls. The objective function rewards the number of different faces visited as well as faces that are more difficult to visit with added bonus for Europa that has a higher scientific interest. Launch from 2020 to 2030, maximum time of flight is 4 years.

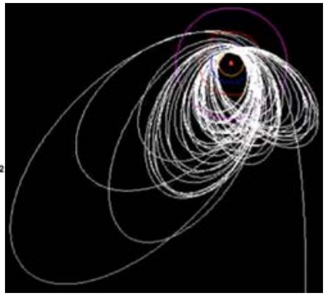
Considered as the most difficult of all GTOC problems released so far, the original plan from the organizer was even more ambitious having the spacecraft depart from the Earth rather than from Jupiter sphere of influence. Winners mapped moons consequently.

The second ranked trajectory, found by a team from the European Space Agency, used an entirely different strategy switching moon very frequently rather than mapping a moon at a time, and yet reached a very similar objective value.

It is debated whether the theoretical maximum score of 324 can be reached.

In 2012 shortly after the competition ended, a solution scoring 316/324 was found by the team from the European Space Agency (and validated by Anastassios Petropoulos from JPL).





10th September 2012

Rank 1: Politecnico di Torino & U. di Roma (Italy)

Rank	J	#Fby	Team	
1	311	123	Team 5	Politecnico di Torino & U. di Roma "Sapienza" Italy
2	308	141	Team 6	ESA-ACT & Hong Kong Univ. of Science and Technology
3	267	98	Team 2	University of Texas at Austin, USA
4	246	126	Team 4	DLR, Germany
5	240	103	Team 8	State Key Laboratory & Chinese Academy of Sciences
6	178	92	Team 28	Analytical Mechanics Associates, Inc., USA
7	176	84	Team 14/9	Tsinghua University, China
8	163	137	Team 10	The Aerospace Corp., USA
9	154	83	Team 18	University of Colorado, Boulder, USA
10	87	53	Team 3	U. of Jena, Germany & TU Delft, The Netherlands
11	83	23	Team 21	Beihang University, Beijing, China
12	73	17	Team 15	University of Hawaii at Manoa, USA
13	15	3	Team 1	Michigan Technological University, USA
consequential violations in altitudes and dynamics				
	18	10	Team 26	Peking University, Beijing, China
incomplete or discontinuous trajectories or other severe violations				
	xx	~3	Team 13	University of Trento, Italy
	xx	2	Team 24	Francesco Santilli, Turin, Italy

GTOC 7 – “Multi-spacecraft exploration of the asteroid belt”

A mother spacecraft is sent to the main asteroid belt and carries three low-thrust probes that need to be released at appropriate times and gather science on as many asteroid as possible before returning to the mother spacecraft to deliver their findings. The probes must remain at each reached asteroid for a minimum time of 30 days.

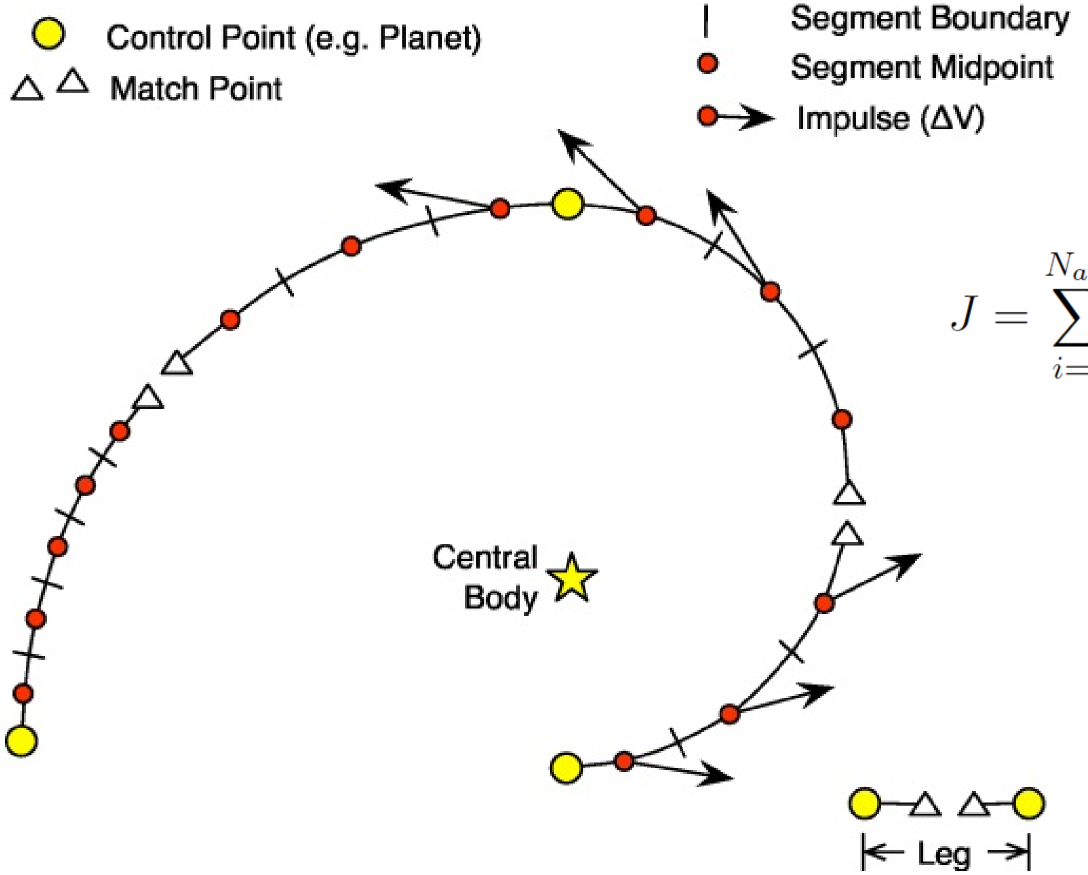
Launch from 2021 to 2031, maximum time of flight of a probe is 6 years, of the mother spacecraft is 12 years.

Rank 1: JPL (USA)

The longest single asteroid sequence valid for a probe and found during the competition had length 14.

It is debated if a sequence of length 15 exists.

A very competitive solution was found by JPL using an Ant Colony Optimization approach.



$$J = \sum_{i=1}^{N_{ast}} \alpha_i$$

Rank	Team No.	Team	J	J', kg
1	19	JPL	36	2450.3
2	22	ACT/ESA-ISAS	35	2502.2
3	3	Un. Texas	35	2493.0
4	21	CAS	32	2509.7
5	4	Tsinghua Un.	32	2457.0
6	36	RIAME-MAI	31	2674.5
7	30	Polimi-Soton-Dinamica	31	2462.9
8	24	Aerospace C.	30	2442.9
9	29	NASA Langley-An.Mech.Ass	29	2875.4
10	6	Colorado Un.	28	2737.1
11	15	Beihang Un.	27	2537.5
12	10	Xi'an SCC	27	2532.3
13	8	CASE-NUDT	27	2529.3
14	13	Odyssey S.R.	26	2736.9
15	17	Beijing ACC	26	2539.2
16	11	Nanjing Un.	25	2897.2
17	28	NASA Goddard-Un.Ill.-ai Sol.	25	2586.0
18	23	Math. Opt.	24	2818.8
19	9	Un. Trento	21	2910.0
20	5	Michigan T. Un.	20	3434.1
21	2	DLR	19	3261.1
22	7	Beihang Un.	18	2567.5
23	12	Telespazio	15	2951.3
24	14	Un. Roma	13	3586.4
-	19	Cal. Poly	3[a]	2450.3
-	32	Nanjing Un.	-[b]	-
-	20	Nanjing Un.	-[c]	-

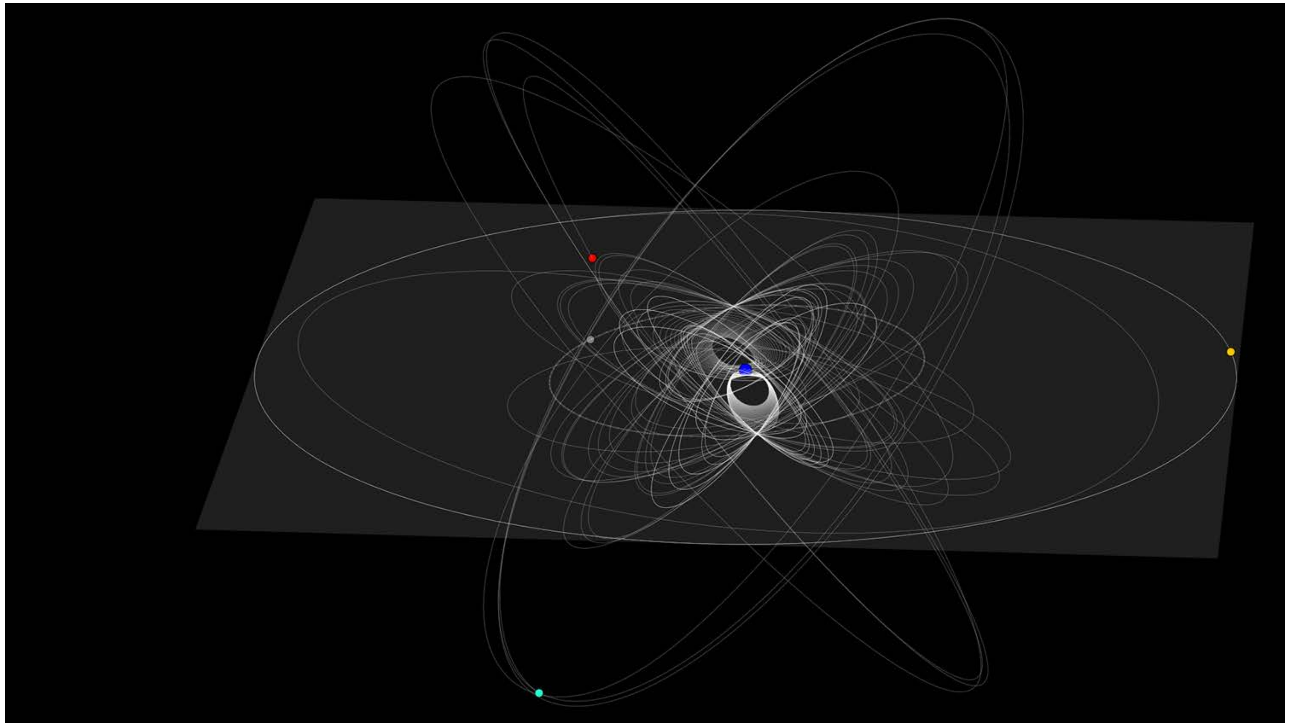
[a] uncorrect body positions, unacceptable solution
[b] probes do not return to mothership (18 asteroids visited), unacceptable solution
[c] unreadable solution files, unacceptable solution

GTOC 8 – "Very-Long-Baseline Interferometry"

$$J = \sum_{\substack{\text{all} \\ \text{observations}}} Ph\left(0.2 + \cos^2\delta\right)$$

The theme chosen for this competition is "high-resolution mapping of radio sources in the universe using space-based Very-Long-Baseline Interferometry (VLBI)". Three spacecraft depart from the Earth and need to perform interferometric measurements of one of 420 radio sources. A measurement can be made when the three spacecraft lie on a plane whose normal points towards the radio source. Moon gravity assists and low-thrust propulsion can be used to target each interferometric measure.

Rank 1: ACT-ISAS (Eupore+Japan)



Rank	Team #	Team Name	J (km)	Number of Sources
1	14	ACT-ISAS	146332116.9	17
2	3	Tsinghua	128286317.0	22
3	22	PolitoUniromaTAS	111533739.2	18
4	10	StateKeyLab	105402381.0	14
5	24	AMA-LaRC	82012271.5 ^{p}	13
6	2	CU	76301536.2	16
7	15	DLR	74973406.1	11
8	18	AerospaceCorp	61032221.5 ^{p}	26
9	13	GlasgowJena+	59682715.4	27
10	8	CAS	49272713.8 ^{p,J}	11
11	29	PolimiUPM	35441068.2 ^{v}	46
12	6	Nanjing	23129442.8 ^{p}	16
13	28	Olympio	11913597.4 ^{p,V}	42
14	11	BeijingACC	1927847.8 ^{V,J}	20
15	31	RPI	302220.8	28
16	23	WVU	255469.4 $^+$	21
17	4	Brazil	82056.8 ^{v}	15
Incomplete submissions, not ranked				
-	16	CalPoly	683.7	39

^{p} *Minor corrections to the P weights.*

^{v} *Minor violations of dynamics and constraints.*

^{V} *Moderate violations of dynamics and constraints.*

^{j} *Moderate downward revision of J.*

^{J} *Significant downward revision of J. Smallest side used instead of smallest altitude.*

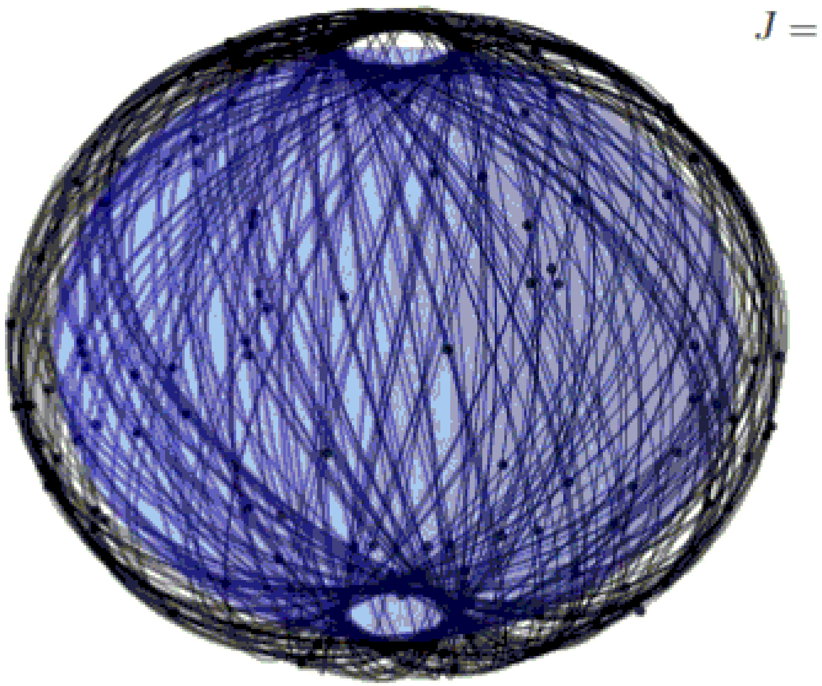
$^+$ *J revised upwards — reported h values were too low.*

18th March 2015

GTOC 9 – "The Kessler Run"

The theme chosen for this competition was active space debris removal and the competition was named "The Kessler Run". It is imagined that in the year 2060 a serious explosion triggered the Kessler effect compromising the Sun-synchronous orbital environment. Fortunately, not all is lost, as scientists isolate a set of 123 orbiting debris pieces that, if removed, would allow to restore the orbital environment functionalities. Multiple missions have to be designed that cumulatively remove all the debris pieces. Each mission cost depends on the spacecraft mass and a base increasing cost.

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



Rank 1: JPL (USA)

The Acta Futura Special Issue

Table 1: Solution Rankings for the Kessler Run (GTOC9)

Rank	Team Name	Missions	Removed	J in MEUR
1	Jet Propulsion Laboratory	10	123	731.2756
2	NUDT Team	12	123	786.21452
3	XSCC-ADL	12	123	821.37966
4	Tsinghua-LAD	12	123	829.57987
5	NPU	13	123	878.99821
6	Strathclyde++	14	123	918.9808
7	DLR	14	123	949.85389
8	Missions Learners	14	123	964.51134
9	The Aerospace Corporation	14	123	1004.4860
10	Team Jena	15	123	1022.9063
11	UT Austin	15	122	1044.1787
12	NJU Team	16	123	1047.9685
13	EFLMAN TEAM	14	119	1107.6936
14	CU Boulder	17	123	1150.8439
15	CAS-NUAA	14	123	1182.0632
16	MTU-UoM	16	122	1192.7433
17	NSSC-THU	16	122	1210.3333
18	Brute WORHP	18	123	1229.5475
19	The Goonies	15	122	1238.6396
20	NablaZeroLabs	16	123	1267.7501
21	TYSE	16	123	1336.8590
22	TM	18	123	1490.9659
23	Occitania	22	120	1493.8567
24	ARGoPS	20	123	1512.6017
25	Personal team	23	123	1588.5770
26	GO to space	20	112	1819.1391
27	UofI and Goddard	23	123	1951.6797
28	LSPirates	20	105	2164.2321
29	Astro-ASAP-UC3M	13	85	3141.1951
30	Cal Poly SLO	39	84	4467.8746
31	Team STAR Lab	12	57	4481.7781
32	Nicolas RAVE	13	18	6453.0254
33	National University of Colombia	2	7	6511.5471
34	MeltedCode	1	5	6594.1105
35	AMSS_GTOC	1	4	6619.3569
36	Bremen optimizers	1	2	6760.20

1th April 2007

GTOC 10 – “Settlers of the Galaxy”

To settle the galaxy (100 000 Star systems around the Milky Way):
1) to settle as many stars as possible
2) as uniform spatial distribution as possible
3) as little propulsive velocity change as possible
4) a bonus for earlier submission

Launch from ~now to +10 Myr, maximum time of flight is 90 Myr

$$J = B\left(\frac{N}{1+10^{-4}\cdot N\,(E_r+E_\theta)}\right)\left(\frac{\Delta V_{max}}{\Delta V_{used}}\right)$$

where

$$B = \left(1+\frac{t_{end}-t_{submission}}{t_{end}-t_{start}}\right)^4$$

$$\frac{N}{1+10^{-4}\cdot N\,(E_r+E_\theta)} = \frac{1}{\frac{1}{N}+\frac{E_r+E_\theta}{10^4}}$$

$$E_r = \sum_{k=0}^{30}\left(\frac{f_r(R_k)}{g_r(R_k)}-1\right)^2 \qquad E_\theta = \sum_{k=0}^{32}\left(\frac{f_\theta(\Theta_k)}{g_\theta(\Theta_k)}-1\right)^2$$

$$E_r = \sum_{k=0}^{30}\left(\frac{f_r(R_k)}{g_r(R_k)}-1\right)^2 \qquad E_\theta = \sum_{k=0}^{32}\left(\frac{f_\theta(\Theta_k)}{g_\theta(\Theta_k)}-1\right)^2$$

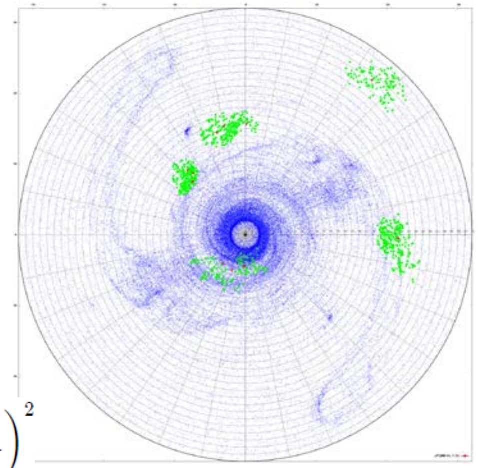
$$f_r(r) = \frac{1}{N}\sum_{i=1}^{N} f(r; r_i, s_r) \qquad f_\theta(\theta) = \frac{1}{N}\sum_{i=1}^{N} f(\theta; \theta_i, s_\theta)$$

$$g_r(r) = \alpha(r)\frac{2r}{R_{max}^2 - R_{min}^2} \qquad g_\theta(\theta) = \beta(\theta)\frac{1}{2\pi}$$

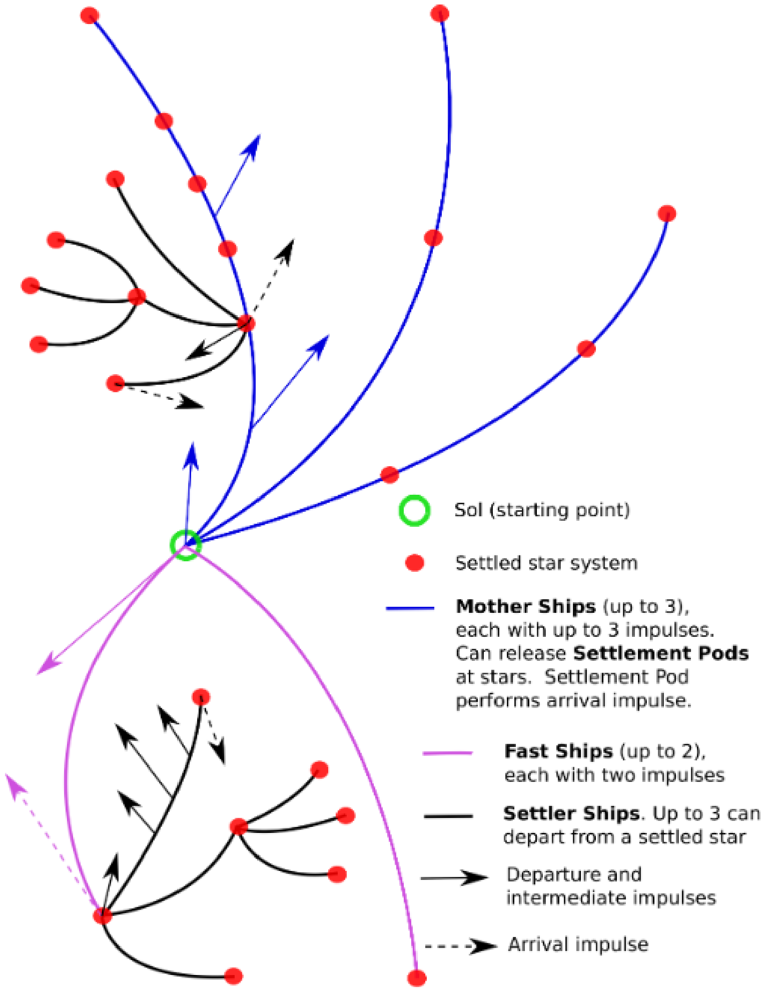
$$\alpha(r) = \begin{cases} 0.5833, r = 2kpc \\ 0.4948, r = 32kpc \\ 1, otherwise. \end{cases} \qquad \beta(\theta) = \begin{cases} 0.5, \theta = -\pi rad \\ 0.5, \theta = \pi rad \\ 1, otherwise. \end{cases}$$

$$R_k = k + 2\,kpc, \quad 0 \le k \le 30 \qquad \Theta_k = -\pi + 2\pi\frac{k}{32}\,rad, \quad 0 \le k \le 32$$

Rank 1: NUDT&XSCC (China)



plane statement; considering existing of the star at any point for tree planning; gradient optimization of the set of Lambert-like boundary problems



Winners: ant colony-optimization

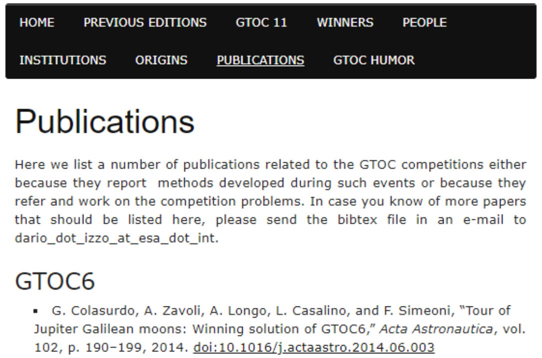
42 команды / 73 представили нетривиальное решение

	Name	N	Best Score
1	NUDT&XSCC	3798	3101
2	Tsinghua LAD - XINGYI	2806	2070
3	ESA-ACT	2652	1996
4	The Aerospace Corporation	2435	1559
5	HIT_BACC	2855	1167
6	CSU	1246	1111
7	Sapienza-PoliTo	1013	946
8	worhp2orb	3235	873
9	1-2-B-#1	1863	802
10	Team Kataskopoi	1352	597
11	NASA GRC	1021	544
12	Team Jena	5	368
13	NASA LaRC	754	360
14	NUDT-G301	1347	360
15	NASA MSFC	2	330
16	UMich	3	321
17	CU Boulder	5	307
18	TM	494	297
19	NUAA-ASTL	5	277
20	IRSIBJ	5	268
21	KAIST	2	242
22	Team BIT	758	237
23	Team Rocket	1	207
24	Toso & Herrera	5	203
25	MSU-RAS-RUDN	968	201

10 editions summary

Champions of Global Trajectory Optimization Competition GTOC

	Year	Champion	Nation
1	2005	Jet Propulsion Laboratory	USA
2	2006	Politecnico di Torino	Italy
3	2007	Centre National d’Etudes Spatiales (CNES)	France
4	2009	Moscow State University	Russia
5	2010	Jet Propulsion Laboratory	USA
6	2012	Politecnico di Torino & U. di Roma "Sapienza"	Italy
7	2014	Jet Propulsion Laboratory	USA
8	2015	European Space Agency’s Advanced Concepts Team & JAXA’s ISAS	Europe & Japan
9	2017	Jet Propulsion Laboratory	USA
10	2019	National University of Defense Technology & Xi’an Satellite Control Center	China

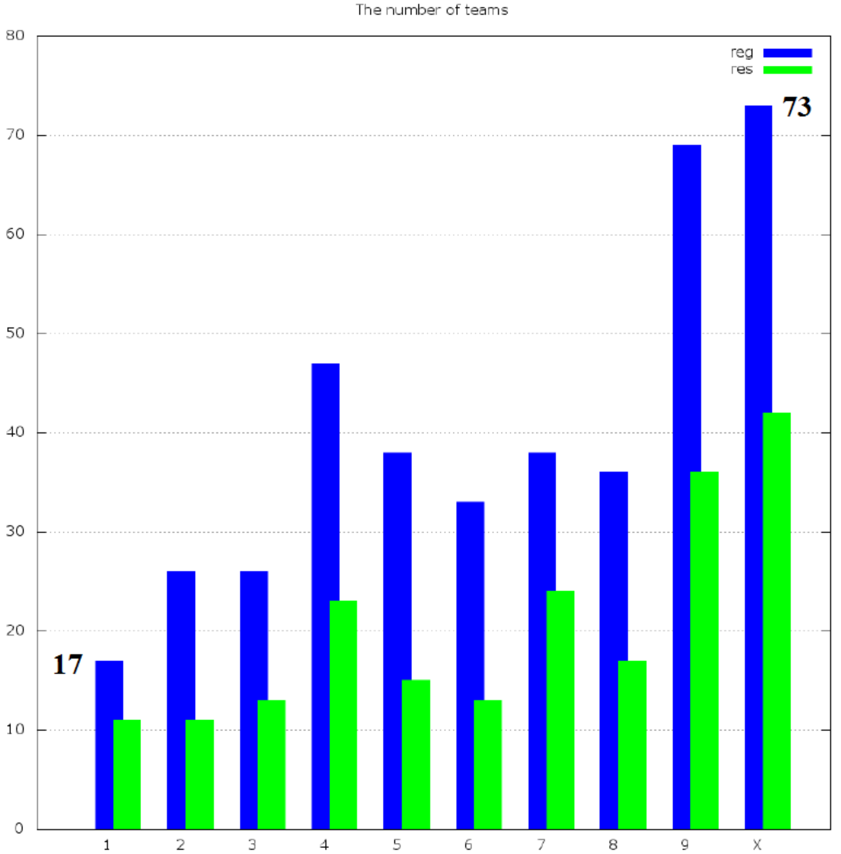

HOME PREVIOUS EDITIONS GTOC 11 WINNERS PEOPLE
INSTITUTIONS ORIGINS PUBLICATIONS GTOC HUMOR

Publications

Here we list a number of publications related to the GTOC competitions either because they report methods developed during such events or because they refer and work on the competition problems. In case you know of more papers that should be listed here, please send the bibtex file in an e-mail to dario_dot_izzo_at_esa_dot_int.

GTOC6

- G. Colasurdo, A. Zavoli, A. Longo, L. Casalino, and F. Simeoni, “Tour of Jupiter Galilean moons: Winning solution of GTOC6,” *Acta Astronautica*, vol. 102, p. 190–199, 2014. doi:10.1016/j.actaastro.2014.06.003



Methodologies adopted by champions:

Numerical schemes and intuitions based on experience + Nasa Mission Analysis Low-Thrust Optimizer;

Manual selection + Indirect method;

Branch-and-bound algorithm + Direct method;

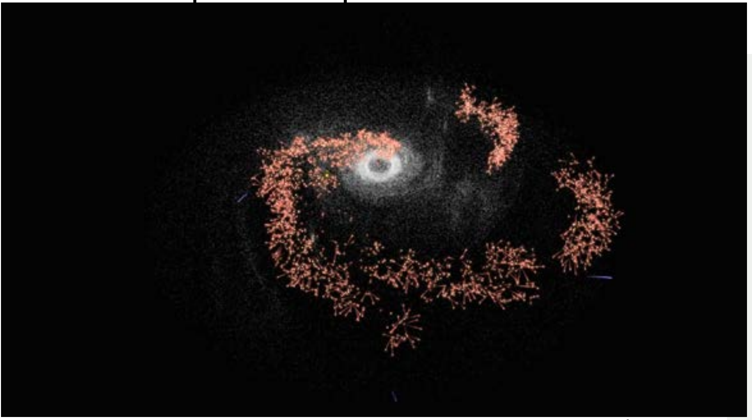
Numerical search + Indirect method;

Backbones strategy with ant colony optimization, particle swarm optimization, and genetic algorithms + Local optimizer;

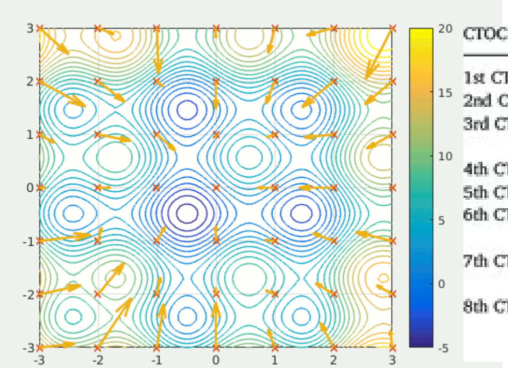
Branch-and-bound algorithm with ant colony optimization algorithms +

Non-liner optimizer Sparse Nonlinear OPTimizer

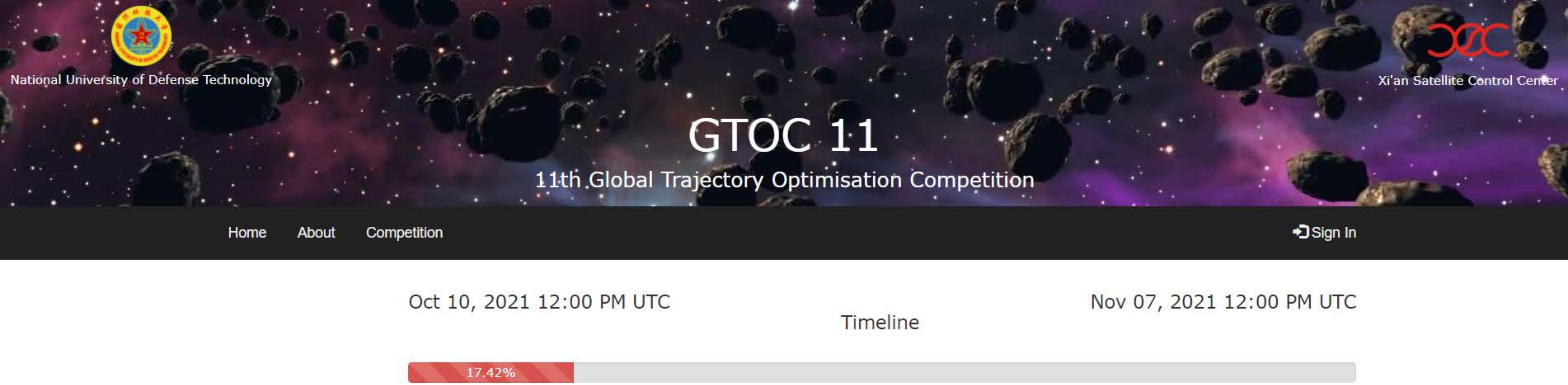
Inspired by the Global Trajectory Optimization Competition, the China Trajectory Optimization Competition (CTOC) was launched by Chinese Society of Theoretical and Applied Mechanics (CSTAM) in 2009



ESA-ACT team GTOC 10 solution, 3rd place



CTOC Series	Problem Description	Champion Team
1st CTOC (2009)	Asteroids sample and return	Academy of Opto-Electronics (AOE), China Academy of Sciences (CAS)
2nd CTOC (2010)	Mars and asteroid multi-target detection	Tsinghua University (TU)
3rd CTOC (2011)	Multi-target multi-task detection of planets and small objects (including Qian Xuesen Star)	Technology and Engineering Center for Space Utilization (CSU), CAS
4th CTOC (2012)	Multi-target multi-mission small object detection	National University of Defense Technology (NUDT)
5th CTOC (2013)	Manned asteroid detection	AOE, CAS; CSU, CAS; Xi'an Satellite Control Center (XSCC)
6th CTOC (2014)	A: Asteroids sample and return (multi-gravitational field)	CSU, CAS
	B: Quickly fly away from the solar system	NUDT; AOE, CAS; CSU, CAS
7th CTOC (2015)	A: Irregular asteroid surface parade and detection	National Space Science Center (NSSC), CAS; XSCC; TU
	B: Reconstruction of the configuration of near-Earth orbit satellite formation	NSSC, CAS; AOE, CAS; XSCC
8th CTOC (2016)	A: Sun synchronous orbit space debris multi-target rendezvous task	Beijing Institute of Technology-Beijing Institute of Electronic System Engineering
	B: Satellite multi-target point observation tasks	Tsinghua Space Center; CSU, CAS



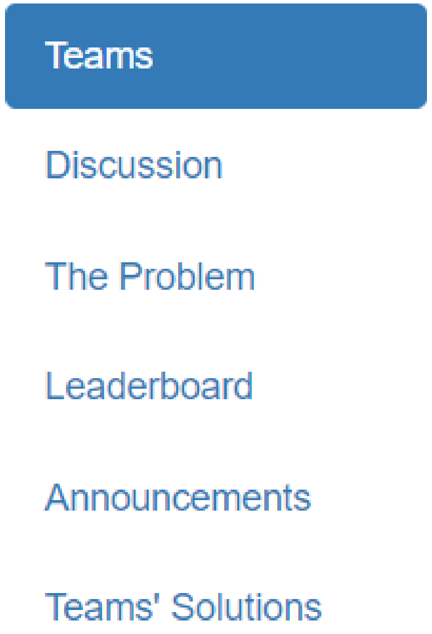
GTOC 11 – "Dyson Sphere" Building

Warm up your rocket (science) **…**

12 September: Registration opens
9 October: Registration closes
10 October: Problem release
17 October: Solution submissions opens
7 November: Solution submissions closes

18 December: GTOC11 virtual meeting (tentative plan)

Official GTOC11 website:
https://gtoc11.nudt.edu.cn



A special issue of the Journal Acta Astronautica is also being organized and will allow the publication of outstanding methods and solutions produced.

Постановка задачи

The task is to design the “Dyson Ring” orbit, to place 12 stations in it, and to carry out a series of missions to transfer asteroids to these stations to maximize the transferred asteroids mass and minimize fuel costs for these missions.

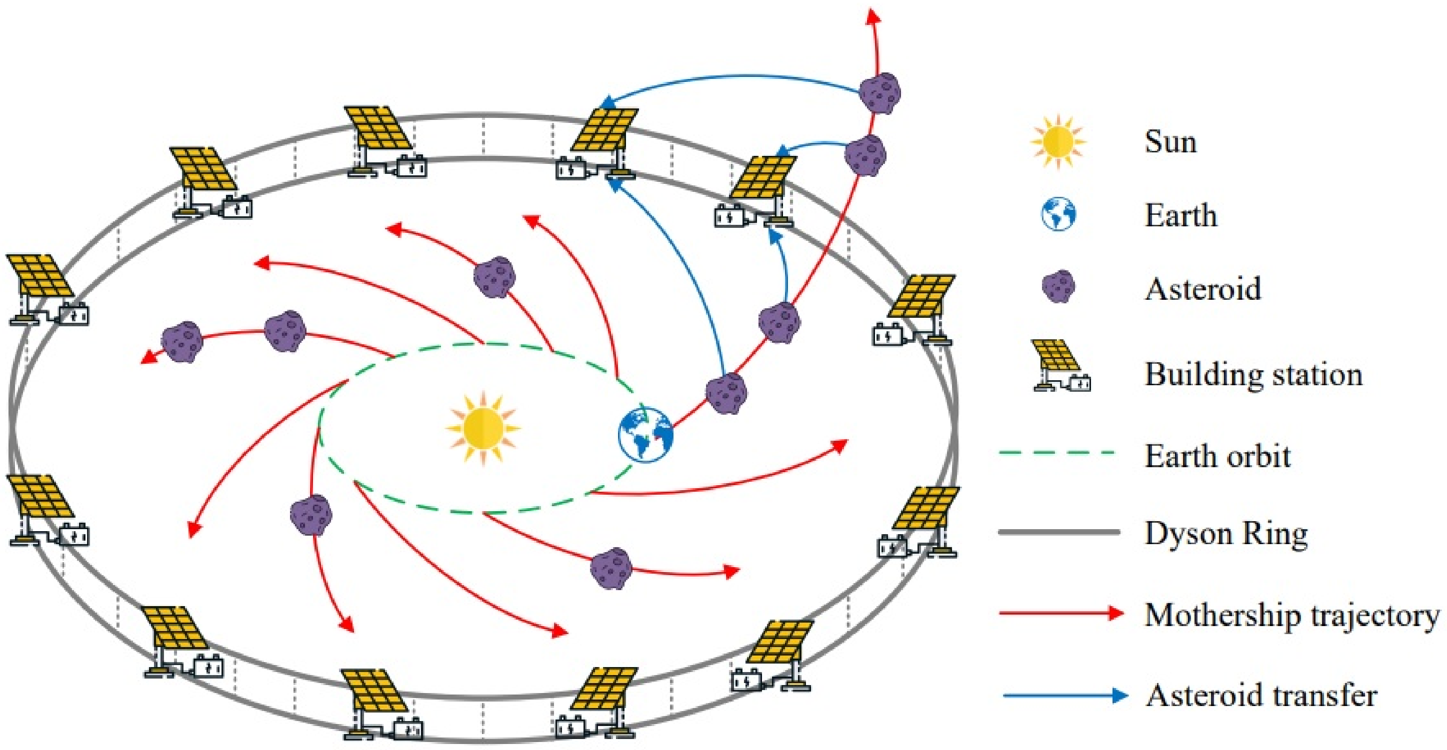


Illustration of the construction of the “Dyson ring”.

Постановка задачи

≤ 10 Motherships

> 83000 asteroids

Their dynamic model:

$$\begin{cases} \dot{\boldsymbol{r}} = \boldsymbol{v} \\ \dot{\boldsymbol{v}} = -\frac{\mu}{r^3}\boldsymbol{r} \end{cases}$$

The maneuvers of the Motherships are impulsive with $\boldsymbol{v}_\infty$ between 0 and 6 km/s.

The launches of the Motherships are between 01.01.2121 00:00:00 UT and 01.01.2141 00:00:00 UT

The asteroid flyby is successive, if the relative velocity $\leq$ 2 km/s. Then the Mothership sets the ATD on the asteroid.

$\leq$ 4 impulsive velocity changes is allowed for Mothership between two successive asteroid flybys.

The ATD can be activated at a proper time to transfer the asteroid to one of 12 building station.

The maneuvers of the asteroids (provided by the ATD) are modeled as continuous-thrust maneuvers with a fixed magnitude of acceleration 1e-4 m/s2 . Then the mass of the asteroid decreases:

$$\dot{m} = \alpha \cdot m_0^{ast} \quad \text{where} \quad \alpha = \text{1e-9 s}^{-1}$$

$$m^{ast}(\Delta t) = m_0^{ast} - \dot{m} \cdot \Delta t$$

Оптимизируемый функционал

$$J = B \cdot \frac{10^{-10} \cdot M_{\min}}{a_{Dyson}^2 \sum_{k=1}^{10} \left(1 + \Delta V_k^{Total} / 50\right)^2}$$

where $B = 2 - \sqrt{1 - \left(1 - \frac{t_{submission} - t_{start}}{t_{end} - t_{start}}\right)^3}$ is the bonus for earlier submission,

a_{Dyson} is the radius of Dyson sphere,

ΔV_k^{Total} is the sum of all ΔV used by k[th] Mothership,

$M_{\min} = \min\{M_j \mid j = 1, 2, ..., 12\}$,

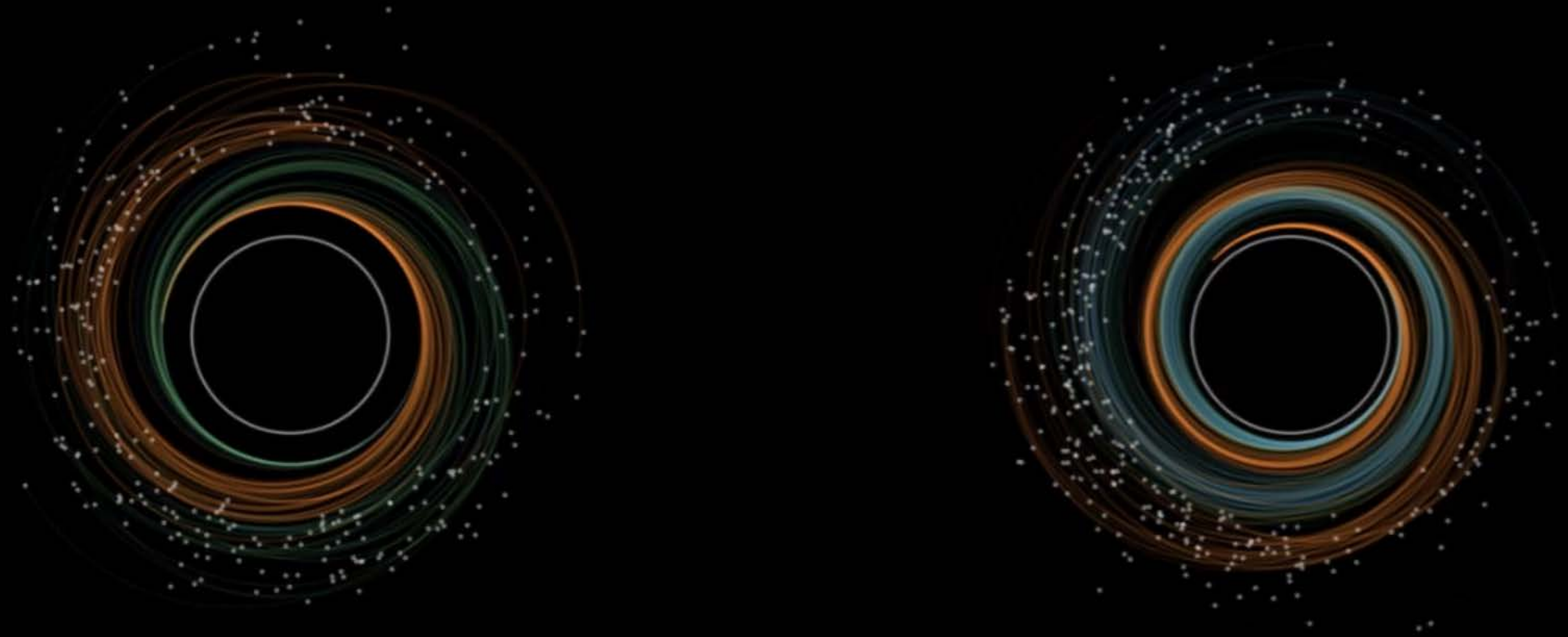
where $M_j = \sum_{i=1}^{n_j} m_{ij}^{ast} \quad j = 1, 2, ..., 12$,

where n_j is the number of the asteroids at the j[th] station

m_{ij}^{ast} is the remaining mass of the i[th] asteroid at the j[th] station

ACT&Friends: 19.88

TsinghuaLAD&509: 19.88



TsinghuaLAD&509 won the competition and reached 1.1 Astronomical Units with 388 asteroids

GTOC 11 best result

Результаты 11-х соревнований

1) Name: TsinghuaLAD&509
Affiliation: Tsinghua University, School of Aerospace Engineering; Shanghai Institute of Satellite Engineering
Location: Beijing, China; Shanghai, China
Members: Zhong Zhang, Nan Zhang, Xiang Guo, Di Wu, Xuan Xie, Jinyuan Li, Jia Yang, Shiyu Chen, Fanghua Jiang, Hexi Baoyin; Haiyang Li, Huixin Zheng, Xiaowen Duan

2) Name: ACT&Friends
Affiliation: ESA Advanced Concepts Team; Friends
Location: NL; JP
Members: Dario Izzo, Marcus Märtens, Anne Mergy, Emmanuel Blazquez, Moritz van Looz, Pablo Gomez, Giacomo Acciarini; Chit Hong Yam, Javier Hernando Ayuso, Yuri Shimane

3) Name: theAntipodes
Affiliation: University of Auckland - ISAE-SUPAERO - University of Surrey - University of Southampton
Location: Auckland and Europe
Members: Roberto Armellin, Laura Pirovano, Minduli Wijayatunga, Adam Evans (University of Auckland); Alberto Fossa, Andrea Bellome, Thomas Caleb (ISAE-SUPAERO); Xiaoyu Fu Danny Owen (University of Surrey); Laurent Beauregard (ESOC); Alex Wittig, Cristina Parigini (University of Southampton); Joan-Pau Sanchez Cuartielles (ISAE-SUPAERO)

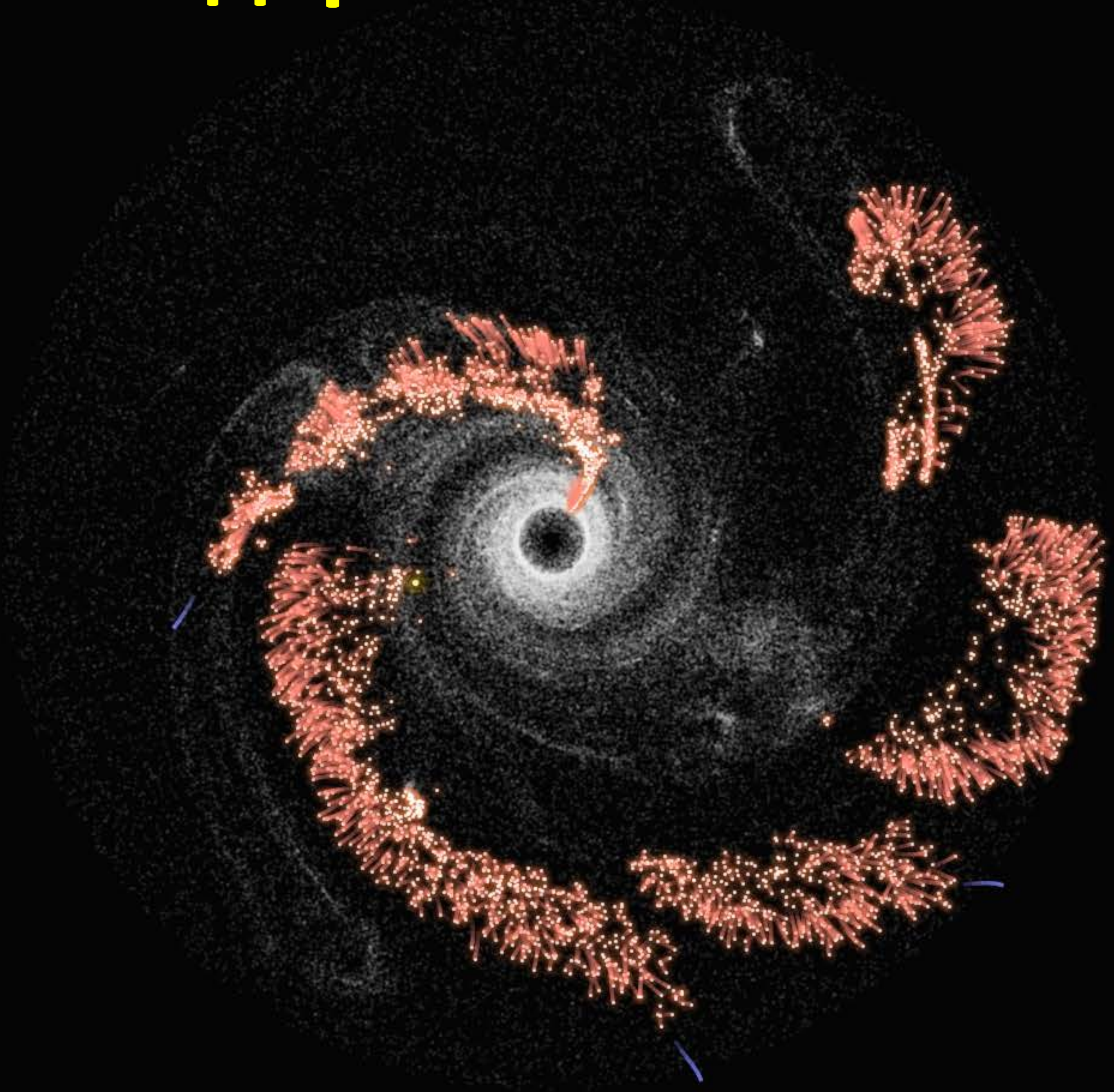
- **Суперкомпьютер**

Соревнования завершились 7 ноября, в тот же день, когда была опубликована задача 1-х соревнований GTOC в 2005. В тех первых соревнованиях команда из Университета Tsinghua, School of Aerospace Engineering, которая выиграла 11-е соревнования, участвовала и заняла последнее место.

	Name	Submissions	Mmin, N	Best Score
1	TsinghuaLAD&509	11	1.81364e+15, 388	8443.630600
2	ACT&Friends	5	2.0125e+15, 301	6359.724900
3	theAntipodes	44	1.27672e+15, 293	5992.298400
4	UT Austin	5	1.13283e+15, 235	5885.469300
5	ASRL	34	1.10046e+15, 209	5525.388800
6	The Eccentric	12	1.89224e+15, 346	5487.543400
7	HIT	21	1.08546e+15, 250	5208.346300
8	GHWZZ	1	1.50229e+15, 294	4794.468600
9	ASTL-NUAA	7	1.03068e+15, 213	3735.160200
10	Team_BIT&ITNS	6	8.00267e+14, 199	3532.704400
11	Pursuance Team	6	7.20367e+14, 157	3277.996400
12	DLR	16	9.00578e+14, 133	3249.373900
13	IDRL & ECNS	5	9.67251e+14, 160	3223.901300
14	BUAA_ADMLab	3	1.02691e+15, 185	2729.973500
15	BUAA	2	9.31363e+14, 174	2622.122400
16	TeamJena	2	5.9348e+14, 138	2376.259800
17	AU-LU	3	5.49777e+14, 148	1556.591200
18	The Aerospace	1	4.07086e+14, 71	694.957730
19	ACSER	2	8.82037e+13, 12	250.949330
20	Iowa State University	5	1.07086e+14, 51	150.872700
21	ALICE	1	1.0712e+14, 12	135.021510
22	Space Buffaloes	1	6.07828e+12, 12	55.398206
23	ASFC-BUAA	1	2.83589e+13, 12	13.962322

23 команды / 94 представили нетривиальное решение

Благодарю за внимание!



GTOC 10 best result