GLOBAL OPTIMIZATION OF INTERPLANETARY TRAJECTORIES IN THE PRESENCE OF REALISTIC MISSION CONSTRAINTS

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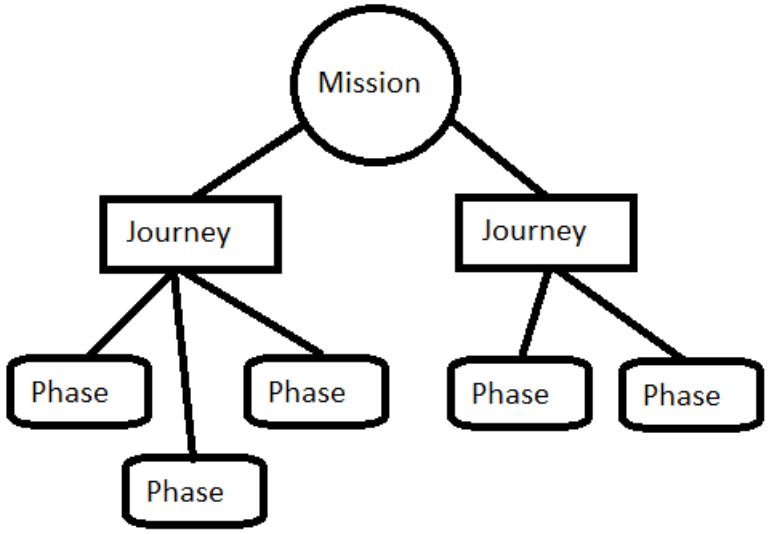
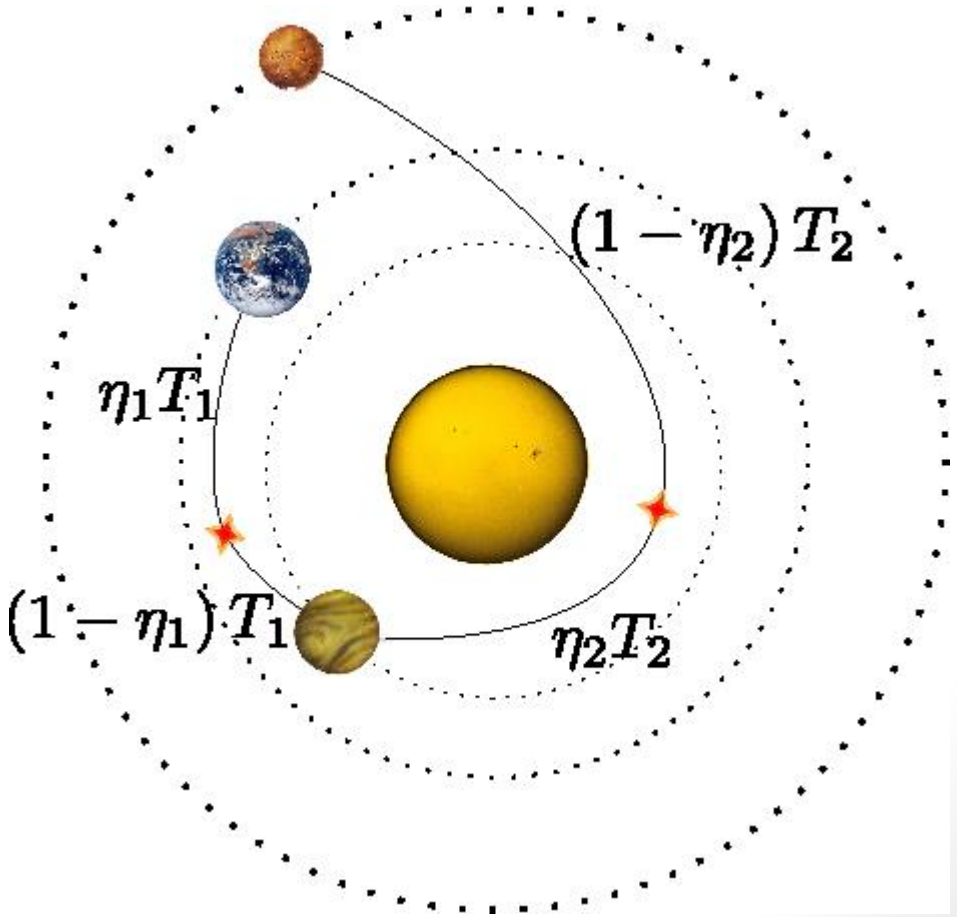
Overview

- MGA-1DSM
- Developed Algorithms
- Test Problems
- Results

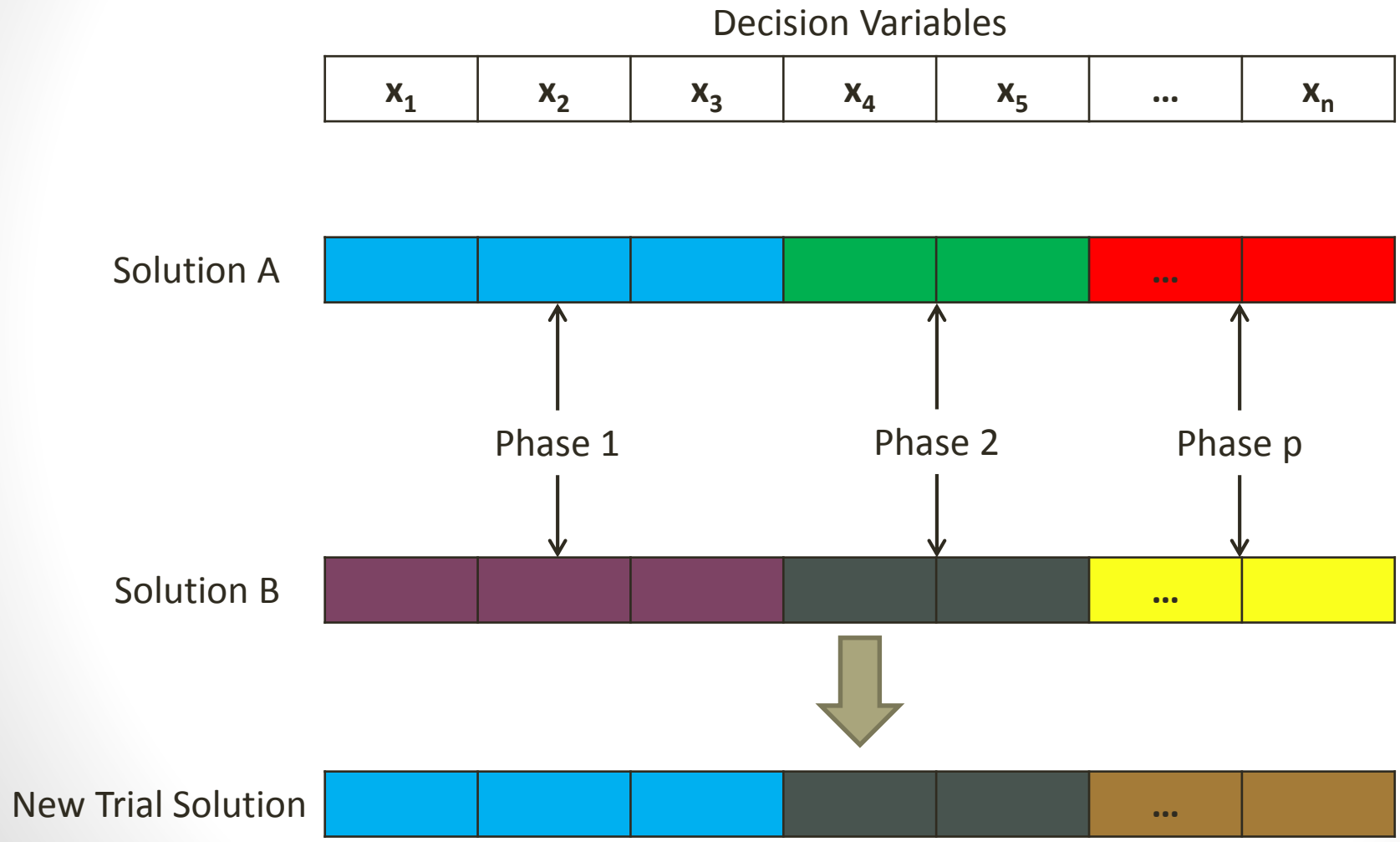
MGA-1DSM

- Multiple Gravity Assist with 1 Deep Space Maneuver



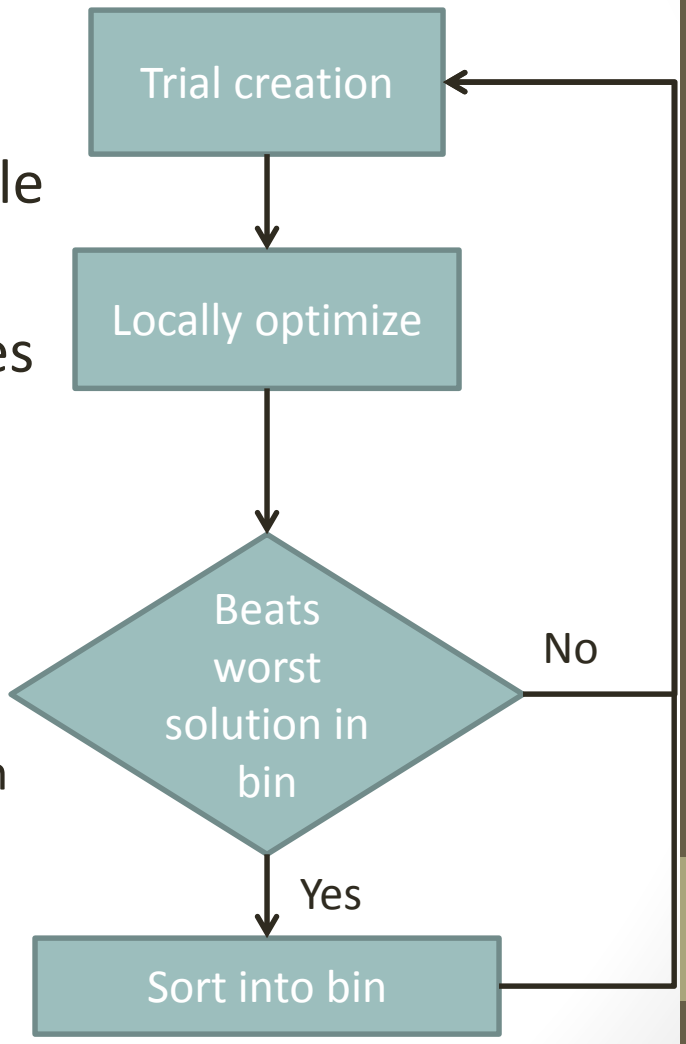


Phase-Wise Gene Recombination



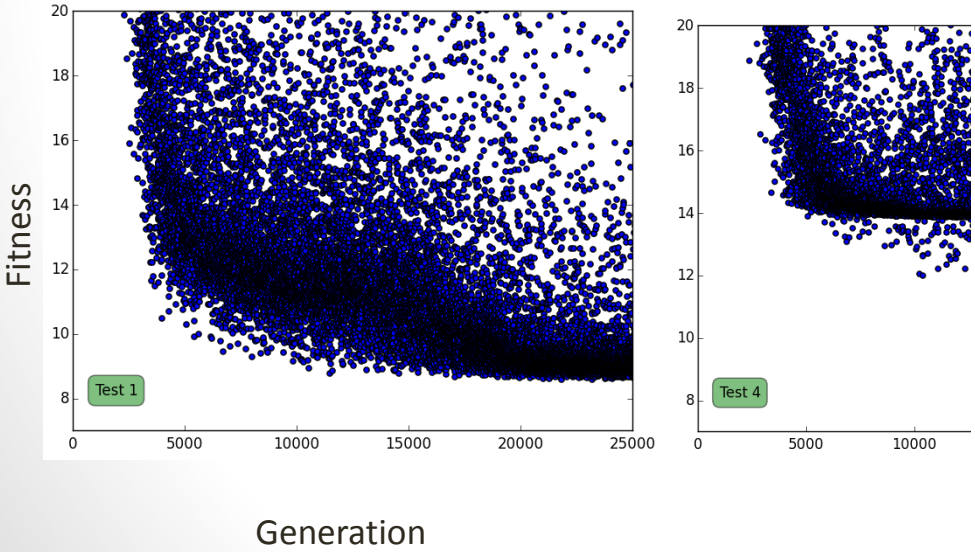
Phase Genetic Solver

- Single trial evaluations
- Trial creation by Phase-wise GA-style or DE-inspired recombination
- “Bin” repository structure – requires an initialization period
- Non-exclusionary “Kill Distance”
- Population collapse mechanic
- Main loop
  - Creation – Probabilistic switch between GA and DE creation types
  - Locally optimize
  - Submit to repository
  - Repeat



Phase Genetic Solver – Population Collapse

- Likelihood of producing better solutions increased as the bin fills with feasible solutions
- Fitness avalanche observed if necessary elements exist in population
- If such material is missing, the bin convergences in fitness space
- Proliferation of breakthrough genetic information moves evolution out of the local optimum



Test Problems

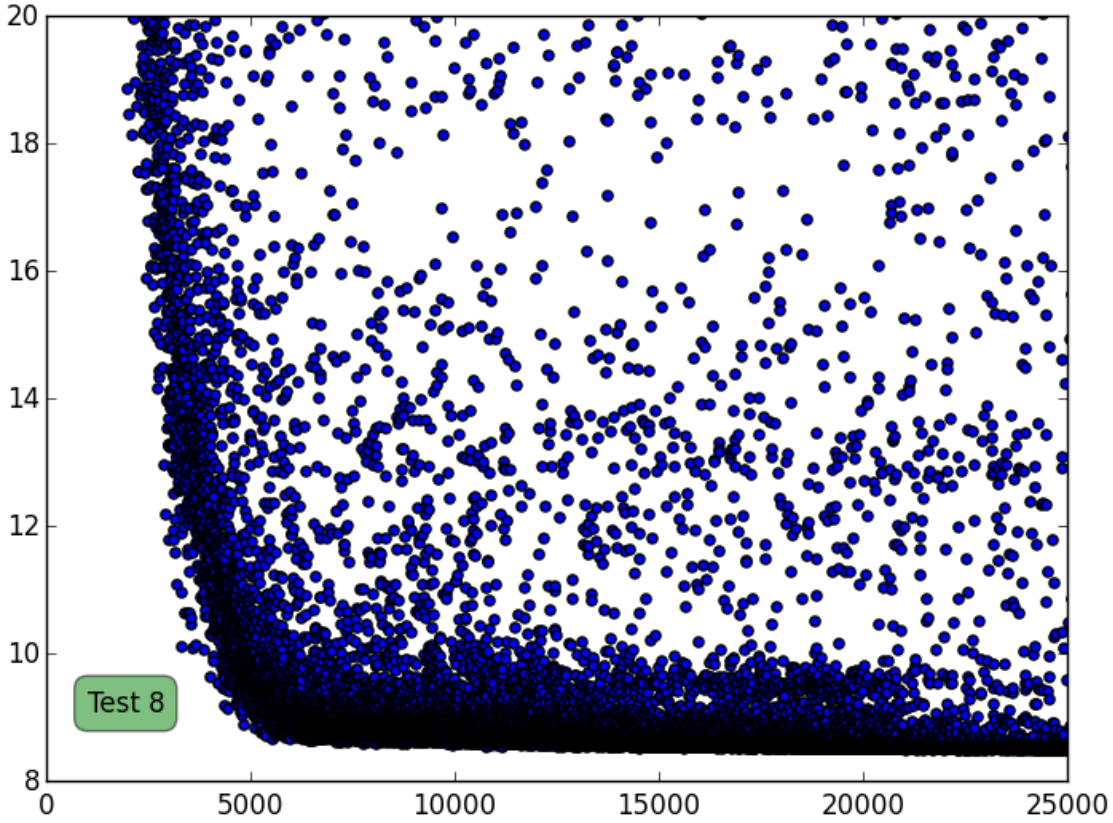
- ESA GTOP Database inspired problems
  - Cassini 2
  - Messenger Reduced
- Real-world problems
  - OSIRIS-REx with 90° spacecraft target Sun angle
  - OSIRIS-REx with 45° spacecraft target Sun angle

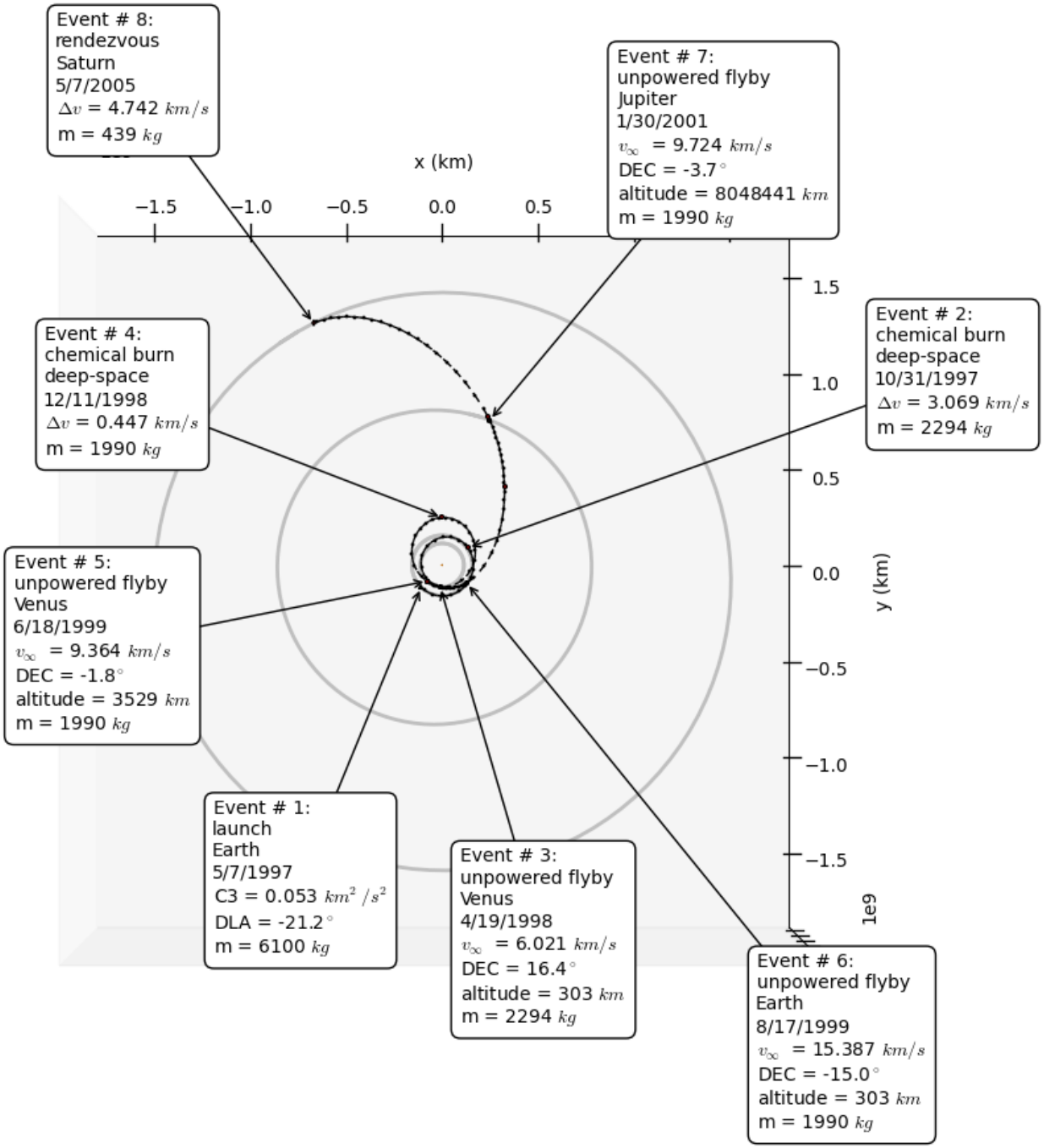
Cassini 2

- Academic model problem based on the Cassini mission
- Bounded time of flight
- Single journey from Earth to Saturn with a fly-by sequence of: Venus, Venus, Earth, Jupiter
- Rendezvous condition at Saturn
- Objective function: minimize Δv

Results – Cassini 2

- Total Δv : 8.4878
- Flight time (y): 8.0000




Event # 8:
rendezvous
Saturn
5/7/2005
Δv = 4.742 km/s
m = 439 kg
Event # 7:
unpowered flyby
Jupiter
1/30/2001
v_∞ = 9.724 km/s
DEC = -3.7°
altitude = 8048441 km
m = 1990 kg
Event # 4:
chemical burn
deep-space
12/11/1998
Δv = 0.447 km/s
m = 1990 kg
Event # 2:
chemical burn
deep-space
10/31/1997
Δv = 3.069 km/s
m = 2294 kg
Event # 5:
unpowered flyby
Venus
6/18/1999
v_∞ = 9.364 km/s
DEC = -1.8°
altitude = 3529 km
m = 1990 kg
Event # 1:
launch
Earth
5/7/1997
C3 = 0.053 km^2/s^2
DLA = -21.2°
m = 6100 kg
Event # 3:
unpowered flyby
Venus
4/19/1998
v_∞ = 6.021 km/s
DEC = 16.4°
altitude = 303 km
m = 2294 kg
Event # 6:
unpowered flyby
Earth
8/17/1999
v_∞ = 15.387 km/s
DEC = -15.0°
altitude = 303 km
m = 1990 kg
x (km)
−1.5
−1.0
−0.5
0.0
0.5
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
y (km)
1e9

Tested Tunings – Cassini 2

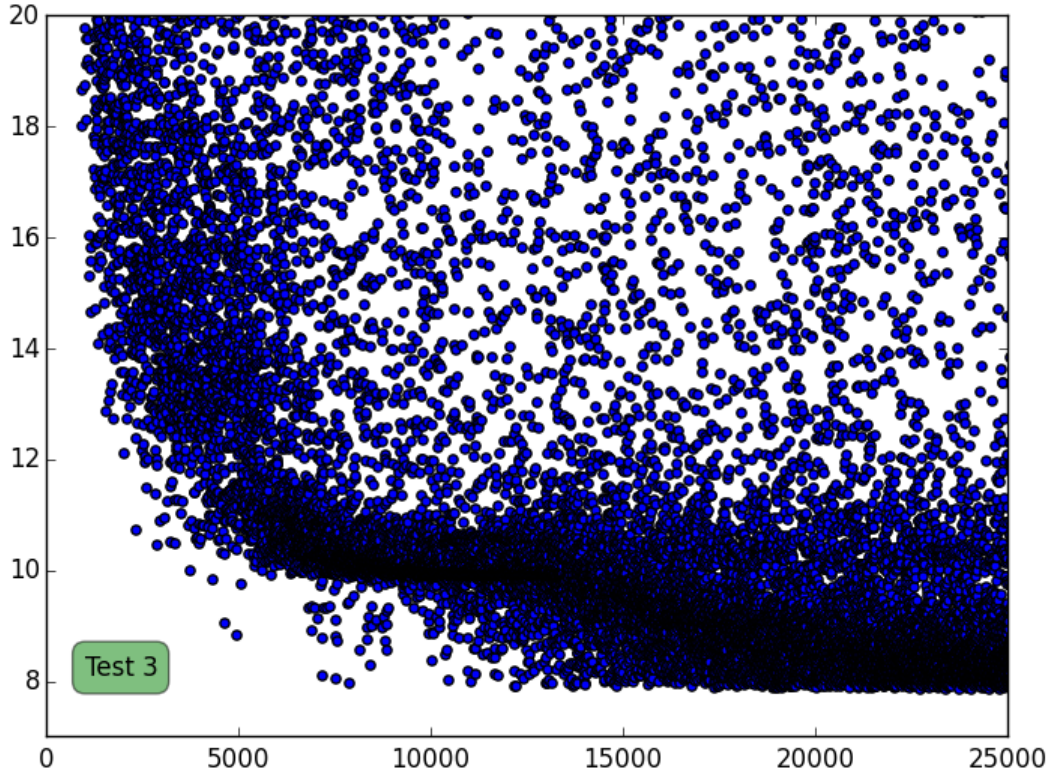
Test Name	Minimum Fitness	Maximum Fitness	Mean Fitness	Standard Deviation of Fitness
NM max iterations = 1000	8.507702203	13.80813145	10.19337892	2.381004889
NM max iterations = 250 & NM stagnation limit = 30	8.495142971	13.80811605	9.129719809	1.583863494
Disabled proximity kill	8.487794692	15.4574581	9.517611548	2.019381623
NM initial step = 0.1	8.519776442	13.80824377	12.40553514	2.155671733
NM repeat = 3	8.491886681	13.80811288	9.534945467	2.055517186
NM initial step = 0.01	8.529650524	13.80819269	9.742230666	1.56202128
Kill distance = 1.25	8.548351326	13.80855295	9.618825493	2.094259801
NM expansion parameter = 5	8.493211225	13.80810881	9.213243008	1.572387353
Kill distance = 0.45	8.489449107	15.64071313	10.84552859	2.550076981
Kill distance = 1.5	8.548151998	8.6373963	8.588254452	0.028344059
DE creation percentage = 60	8.510255988	13.80812768	10.37414168	2.37686051
NM max iterations = 250	8.502856018	13.80823687	10.28526561	2.330492865
Fitness penalty weight = 50	8.510825618	9.445452757	8.696852204	0.354515305
DE creation percentage = 30	8.943567626	16.04331072	13.08227751	2.115409215
DE creation percentage = 80	8.518332019	8.578794109	8.541124301	0.015297718
NM stagnation limit = 50	8.500648814	13.80810493	9.037603714	1.590176354
Fitness penalty weight = 10	8.50422969	44.25559316	17.57454411	11.51069538
Default	8.501509161	15.64214162	11.20484013	2.95955532
DE creation percentage = 70	8.517078919	8.556319048	8.534003909	0.009798648
Kill distance = 2.0	8.638286021	13.87964676	10.2763394	2.346441835
Pareto mutation percentage = 100	8.501850121	11.16184864	8.972233049	0.816102361

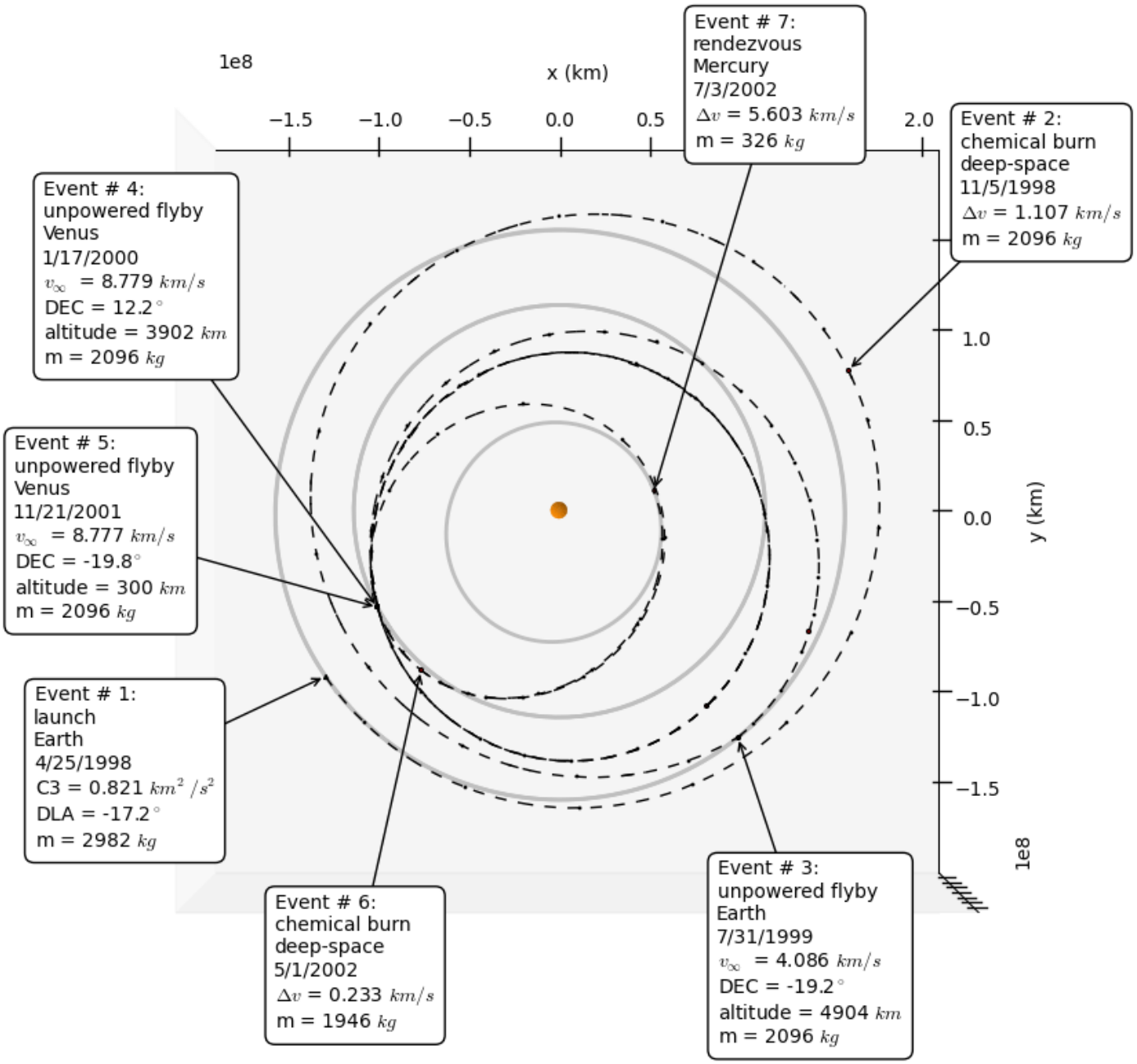
Messenger Reduced

- Academic model problem based on the Messenger mission
- Bounded time of flight
- Single journey from Earth to Mercury with a fly-by sequence of: Earth, Venus, Venus
- Rendezvous condition at Mercury
- Objective function: minimize Δv

Results – Messenger Reduced

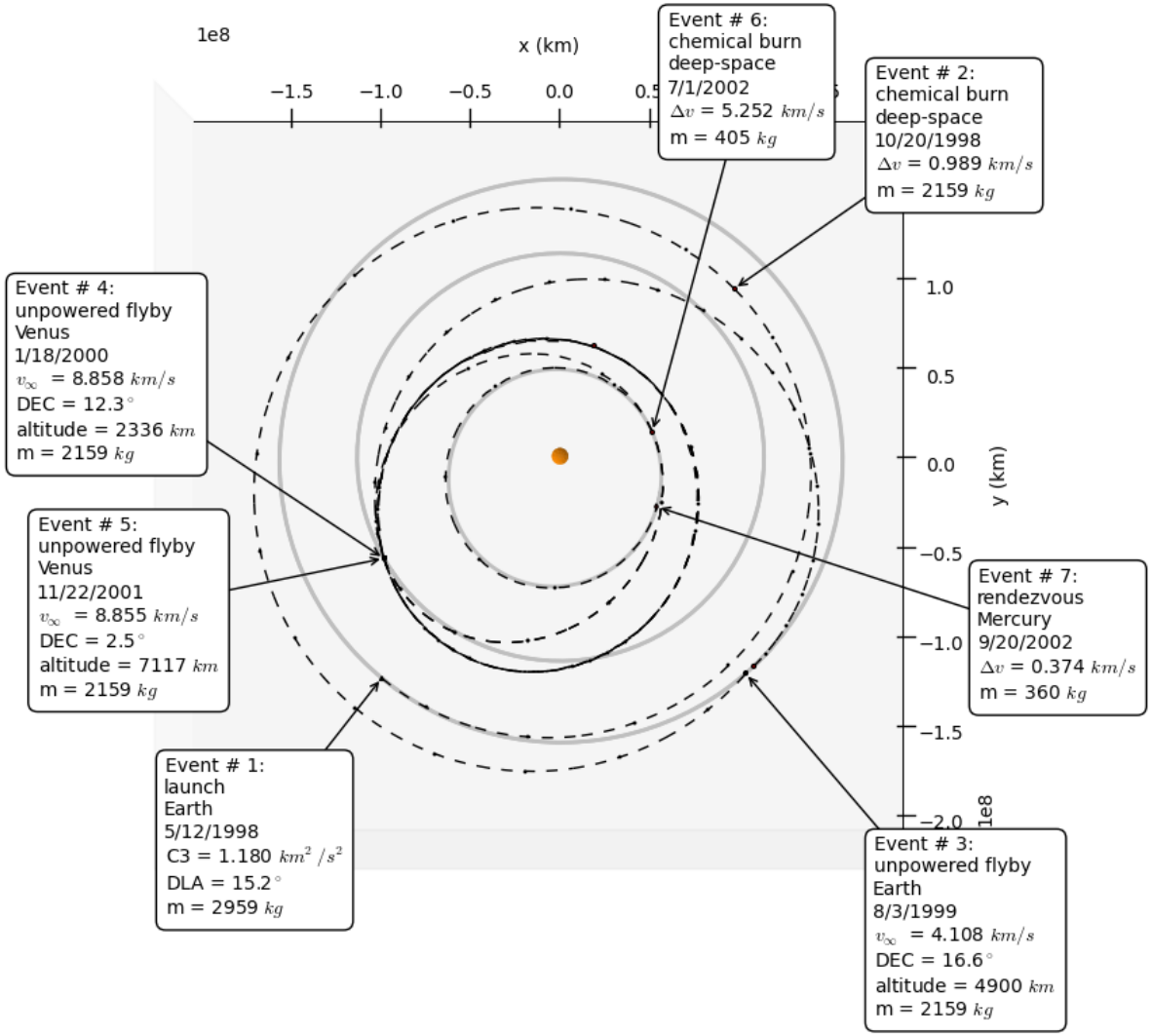
- Total Δv : 7.8483
- Flight time (y): 4.1872




1e8
x (km)
−1.5
−1.0
−0.5
0.0
0.5
2.0
1.0
0.5
0.0
−0.5
−1.0
−1.5
y (km)
1e8
Event # 7:
rendezvous
Mercury
7/3/2002
Δv = 5.603 km/s
m = 326 kg
Event # 2:
chemical burn
deep-space
11/5/1998
Δv = 1.107 km/s
m = 2096 kg
Event # 4:
unpowered flyby
Venus
1/17/2000
v_∞ = 8.779 km/s
DEC = 12.2°
altitude = 3902 km
m = 2096 kg
Event # 5:
unpowered flyby
Venus
11/21/2001
v_∞ = 8.777 km/s
DEC = -19.8°
altitude = 300 km
m = 2096 kg
Event # 1:
launch
Earth
4/25/1998
C3 = 0.821 km^2/s^2
DLA = -17.2°
m = 2982 kg
Event # 6:
chemical burn
deep-space
5/1/2002
Δv = 0.233 km/s
m = 1946 kg
Event # 3:
unpowered flyby
Earth
7/31/1999
v_∞ = 4.086 km/s
DEC = -19.2°
altitude = 4904 km
m = 2096 kg

Results – Messenger Reduced

- Total Δv : 7.7005
- Flight time (y): 4.3597



Tested Tunings – Messenger Reduced

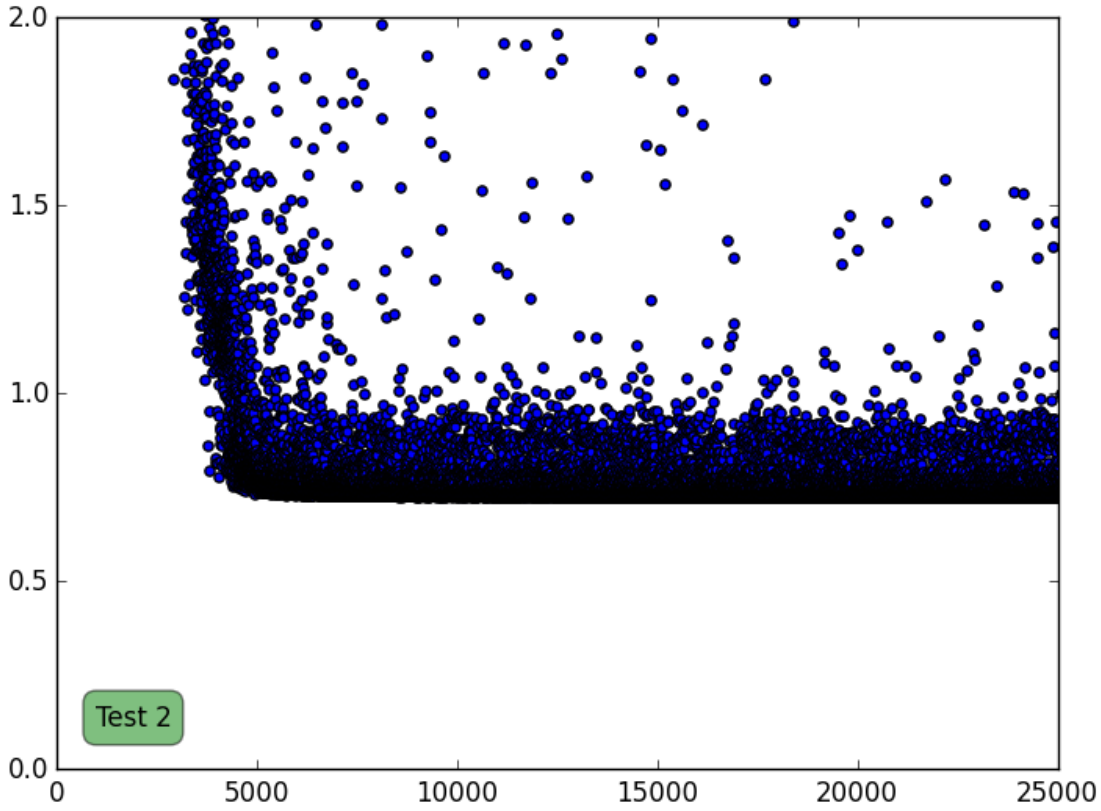
Test Name	Minimum Fitness	Maximum Fitness	Mean Fitness	Standard Deviation of Fitness
DE creation percentage = 30 NM max iterations = 1000 & NM stagnation limit = 100 &	7.700553833	10.077949	8.69836204	0.957901076
Pareto mutation percentage = 100 NM max iterations = 1000 &	7.885601368	9.838366048	8.135282451	0.580954014
NM stagnation limit = 100	7.848294059	9.196548589	8.092378624	0.424963406
Disabled proximity kill	7.883441903	11.46388641	9.370414423	1.286407838
NM max iterations = 1000	7.885493493	11.46414506	8.830137907	1.18791056
NM repeat = 3	7.884693973	10.5763399	8.818799601	0.85652511
DE creation percentage = 70	7.891120342	9.968710382	8.988314296	0.931023514
NM stagnation limit = 50	7.884667061	9.950609605	8.665714852	0.95438583
NM stagnation limit = 100	7.884242668	9.951119188	8.163303062	0.632826718
NM initial step = 0.01	7.883914168	11.46634384	9.96979681	1.206551117

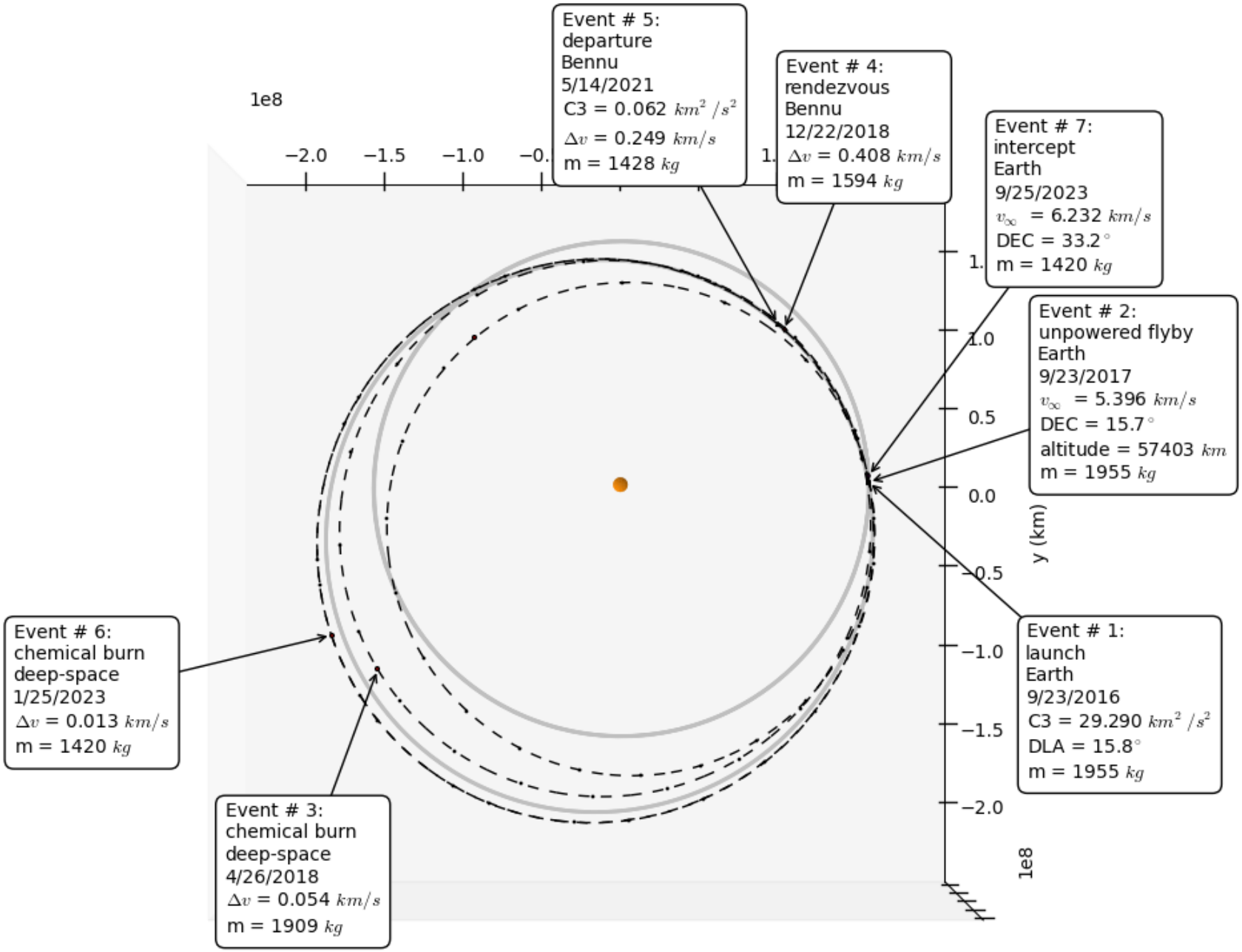
OSIRIS-REx

- 2 Journey Mission
  - Journey 1: Earth to Bennu with 1 Earth fly-by
  - Journey 2: Bennu to Earth
- Bounded allowable spacecraft target Sun angle at Bennu
  - Trial 1: 90°
  - Trial 2: 45°
- Objective function: minimize Δv

Results – OSIRIS-REx 90°

- Total Δv : 0.7238
  - Outbound Δv: 0.4624
- Flight time (y): 7.0041 Launch day: 9-23-2016



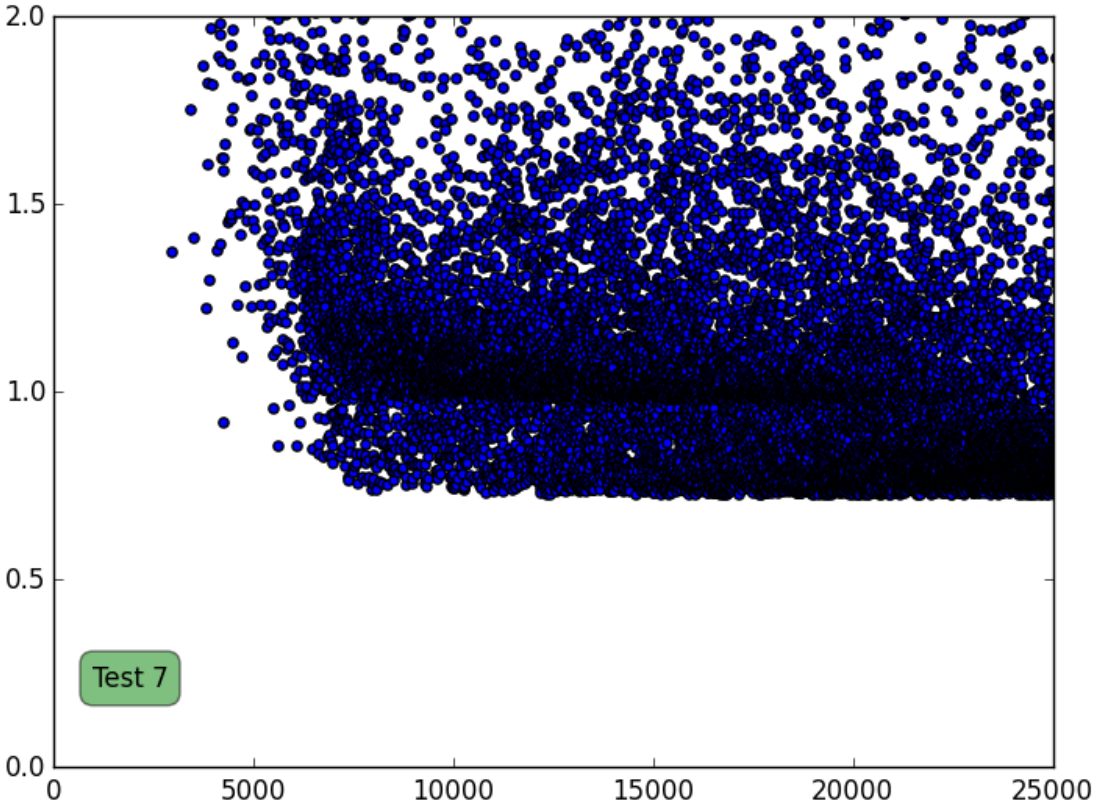

Event # 5:
departure
Bennu
5/14/2021
C3 = 0.062 km^2/s^2
Δv = 0.249 km/s
m = 1428 kg
Event # 4:
rendezvous
Bennu
12/22/2018
Δv = 0.408 km/s
m = 1594 kg
Event # 7:
intercept
Earth
9/25/2023
v_∞ = 6.232 km/s
DEC = 33.2°
m = 1420 kg
Event # 2:
unpowered flyby
Earth
9/23/2017
v_∞ = 5.396 km/s
DEC = 15.7°
altitude = 57403 km
m = 1955 kg
Event # 1:
launch
Earth
9/23/2016
C3 = 29.290 km^2/s^2
DLA = 15.8°
m = 1955 kg
Event # 3:
chemical burn
deep-space
4/26/2018
Δv = 0.054 km/s
m = 1909 kg
Event # 6:
chemical burn
deep-space
1/25/2023
Δv = 0.013 km/s
m = 1420 kg
1e8
−2.0
−1.5
−1.0
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
y (km)
1e8

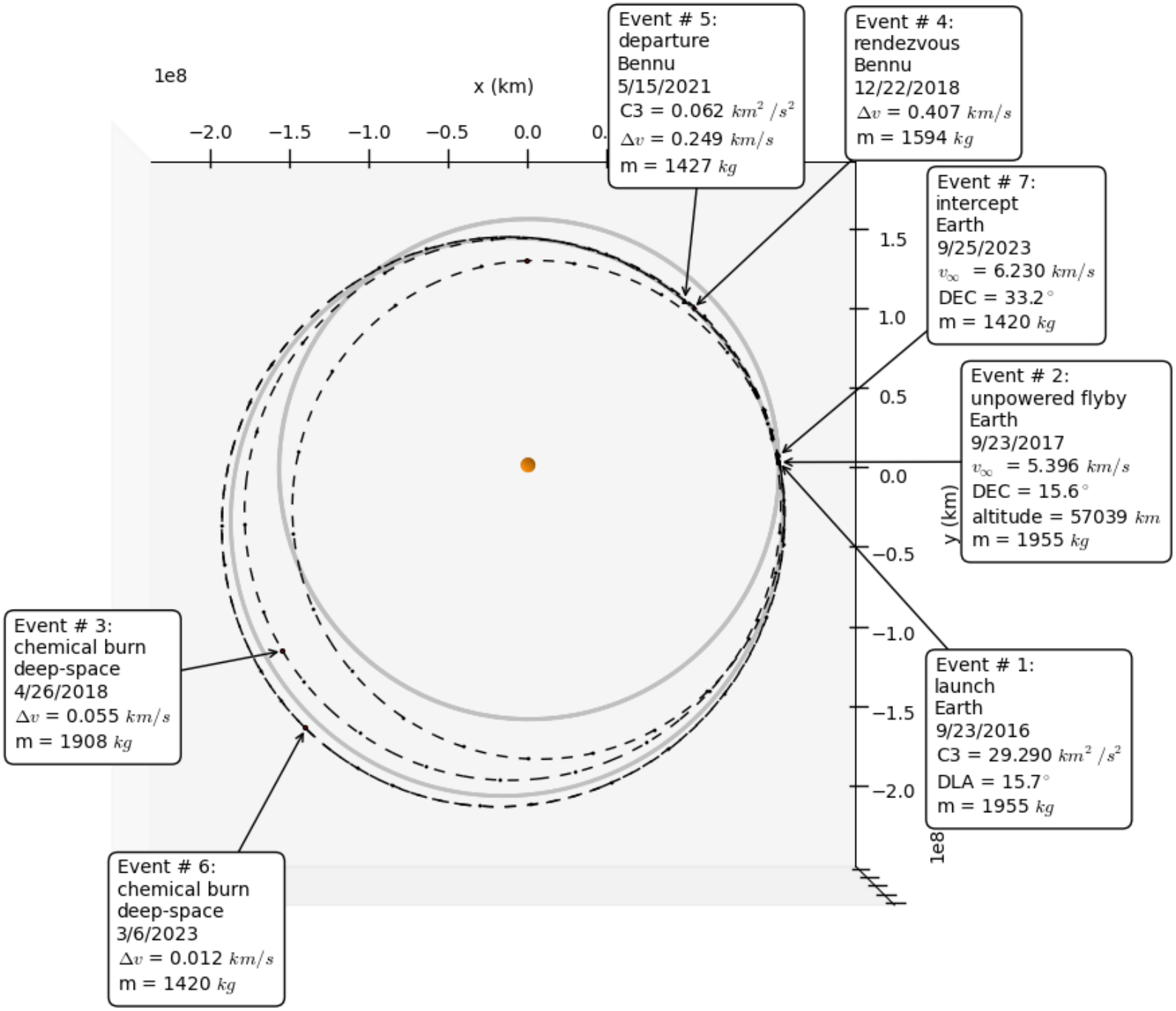
Tested Tunings – OSIRIS-REx 90°

Test Name	Minimum Fitness	Maximum Fitness	Mean Fitness	Standard Deviation of Fitness
Disabled proximity kill	0.723849797	2.932235497	1.173036182	0.68831895
NM initial step = 0.1	0.725279214	1.796980154	0.835174524	0.320672698
NM stagnation limit = 50	0.724487126	1.233349354	0.810434537	0.154609675
NM max iterations = 1000	0.724595703	1.608428143	0.954556275	0.291337706
NM stagnation limit = 100	0.724276918	1.607709109	0.852585628	0.260491888
Kill distance = 1.2	0.725769679	1.288751624	0.802798213	0.16791975
Kill distance = 0.45	0.724017532	1.607853071	0.898080663	0.258426999
DE creation percentage = 30	0.72518409	17.29093509	3.433378663	4.746951776
NM max iterations = 1000 & NM stagnation limit = 100	0.724384127	873.0522079	122.7224839	257.1555035
DE creation percentage = 70	0.725050606	1.609679952	0.831758675	0.26446865
Pareto mutation percentage = 100	0.724466525	1.609754007	0.869859487	0.256750254
Default	0.725657145	3.738515419	1.107804668	0.881684002

Results – OSIRIS-REx 45°

- Total Δv : 0.7241
  - Outbound Δv: 0.4625
- Flight time (y): 7.0040 Launch day: 9-23-2016




Event # 5:
departure
Bennu
5/15/2021
C3 = 0.062 km^2/s^2
Δv = 0.249 km/s
m = 1427 kg
Event # 4:
rendezvous
Bennu
12/22/2018
Δv = 0.407 km/s
m = 1594 kg
Event # 7:
intercept
Earth
9/25/2023
v_∞ = 6.230 km/s
DEC = 33.2°
m = 1420 kg
Event # 2:
unpowered flyby
Earth
9/23/2017
v_∞ = 5.396 km/s
DEC = 15.6°
altitude = 57039 km
m = 1955 kg
Event # 3:
chemical burn
deep-space
4/26/2018
Δv = 0.055 km/s
m = 1908 kg
Event # 1:
launch
Earth
9/23/2016
C3 = 29.290 km^2/s^2
DLA = 15.7°
m = 1955 kg
Event # 6:
chemical burn
deep-space
3/6/2023
Δv = 0.012 km/s
m = 1420 kg
1e8
x (km)
−2.0
−1.5
−1.0
−0.5
0.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
y (km)
1e8

Tested Tunings – OSIRIS-REx 45°

Test Name	Minimum Fitness	Maximum Fitness	Mean Fitness	Standard Deviation of Fitness
Disabled proximity kill	0.794681232	3.797895363	1.64365942	1.101750074
Pareto mutation percentage = 100	0.799880971	6.160661388	1.468606482	1.583540108
NM max iterations = 1000	0.724436189	4.045370978	1.159974362	0.987205563
NM stagnation limit = 100	0.724134498	1.068555671	0.801919046	0.124221252
Default	0.762818765	1.64313778	0.957427469	0.248590476
Kill distance = 1.2	0.800867037	1.834345561	0.943784705	0.309631387
Kill distance = 0.45	0.754246276	5.67378172	1.451568898	1.443897955
NM initial step = 0.1	0.797778251	2.361178032	0.993787507	0.461541481
DE creation percentage = 70	0.798337374	1.084989391	0.879957468	0.105577135
NM max iterations = 1000 & NM stagnation limit = 100	0.795939001	0.96675381	0.836301535	0.065568903
DE creation percentage = 30	0.810500627	13.98726773	2.472446933	3.860479861
NM stagnation limit = 50	0.80221576	2.052751678	0.966982707	0.368824685

Conclusions – FIX

- The Phase Genetic Solver works very well on the chemical mission problems tested
- Tuned problems are solved reliably
- A tuning law has yet to be developed
- This method can be extended to any problem where grouped decision variables have additional meaning

Questions?