A Novel Multi-Spacecraft Interplanetary Global Trajectory Optimization Transcription

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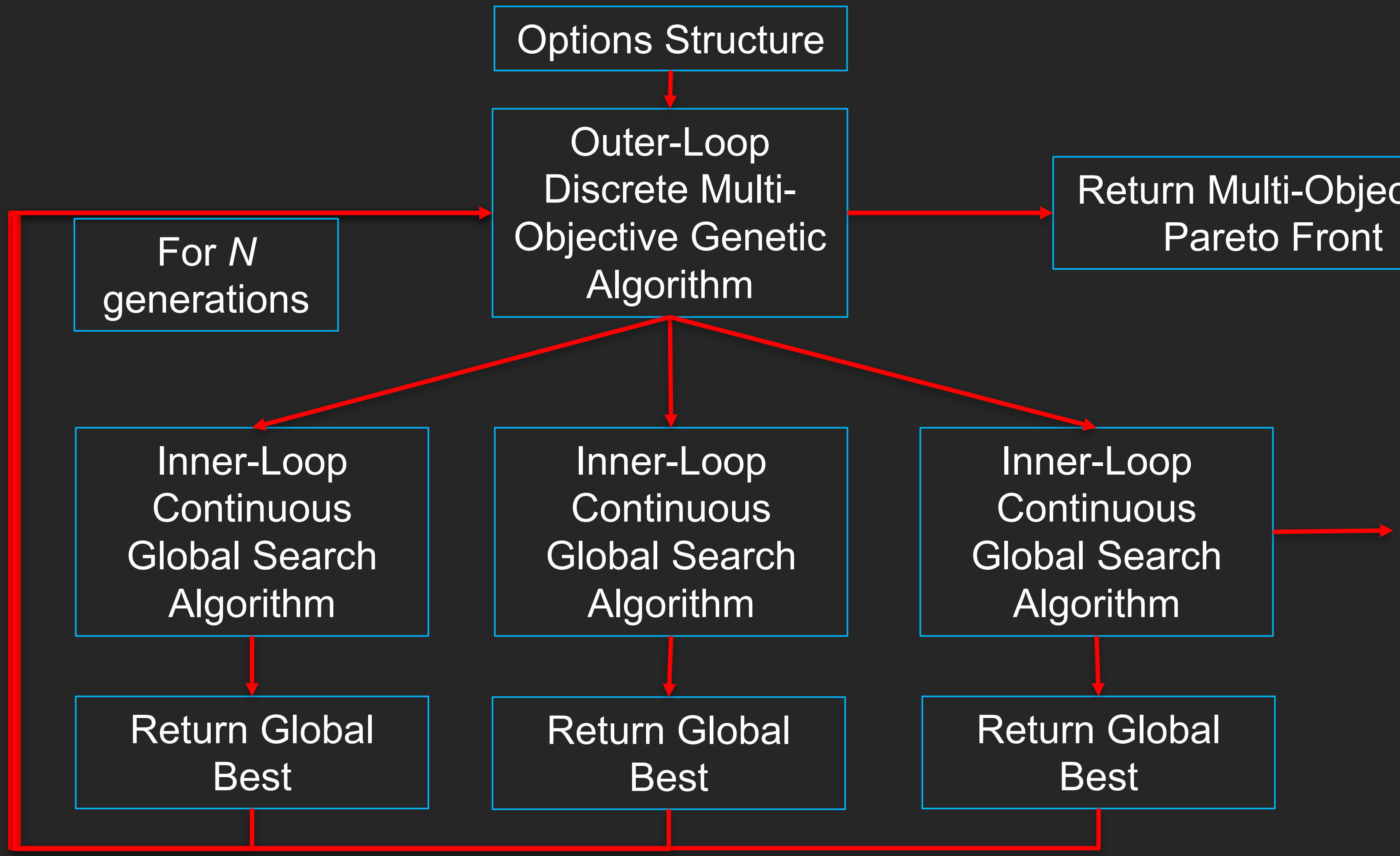
Background

- **Distributed Spacecraft Missions:** multiple spacecraft coordinate to perform shared objectives
- Current approaches for Multi-Vehicle Mission (MVM) design prone to:
  - Laborious iterative steps
  - Treatment of the MVM as multiple, separate sub-problems
  - Poor handling of coordination objectives & constraints
- **No Multi-Objective, *Multi-Agent* Hybrid Optimal Control Problem (MOMA HOCP) mission design platforms**

Overview

1. MOMA HOCP Architecture
2. Coordination Constraints & Objectives
3. Results
   a) Validate basic functionality by reproducing Cassini cruise
   b) Ice Giant Multi-Mission design
4. Future work

MOMA HOCP Formulation



- Version 1: Differential Evolution (DE) algorithm nested within Monotonic Basin Hopper (MBH)
- Version 2: MBH+ `fmincon()`

Outer-Loop Transcription

< HEADER > , < FLYBY SEQUENCE >

$$X = \begin{bmatrix} LW & T_{cap} & C_3 & N_{shfb} & \text{Planet}_{1,1} & \text{Planet}_{1,2} & \text{Planet}_{1,3} & \text{Destination}_1 \\ LW & T_{cap} & C_3 & N_{shfb} & \text{Planet}_{2,1} & \text{Planet}_{2,2} & \text{Planet}_{2,3} & \text{Destination}_2 \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 5 & 2 & 1 & 1 & 10 & 4 & 6 \\ 1 & 5 & 2 & 1 & 2 & 3 & 5 & 7 \end{bmatrix}$$

$$= \begin{bmatrix} \{1/1/2030, 5/1/2030\} & 10\,yr & [50, 60]\,km^2/s^2 & (0\,shfb) & \text{Venus} & \text{NULL} & \text{Jupiter} & \text{Uranus} \\ \{1/1/2030, 5/1/2030\} & 10\,yr & [50, 60]\,km^2/s^2 & (0\,shfb) & \text{Earth} & \text{Mars} & \text{Saturn} & \text{Neptune} \end{bmatrix}$$

Stay Tuned

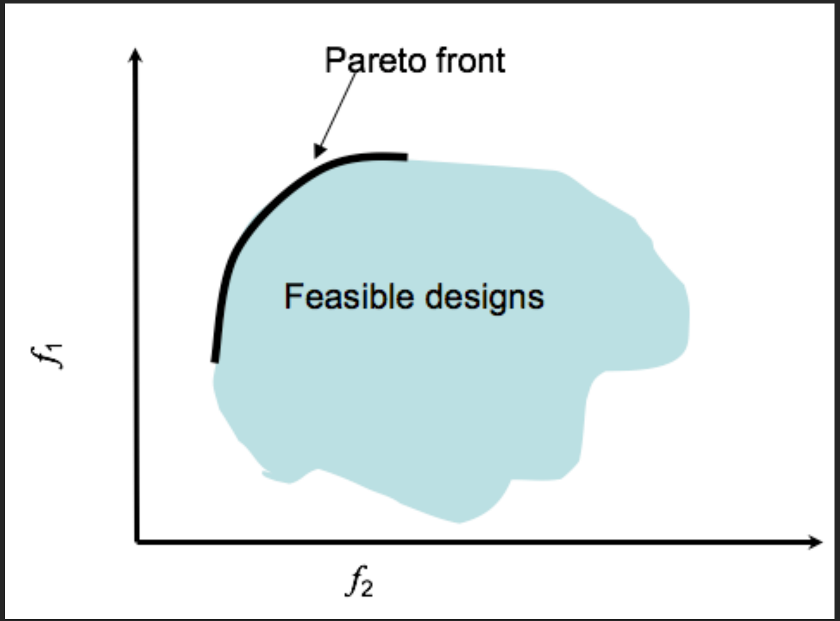
Null Gene **transcription enables insertion & deletion of genes by inner-loop while maintaining fixed chromosome size in outer-loop**[2]

Novel Outer-Loop Constraints

- **Shared Launch Vehicle**
  - Multiple spacecraft constrained to share a launch vehicle
  - $[LW_i, C_{3,i}, RLA_i, DLA_i]$ identical for $i = 1,2,\ldots,N$ spacecraft in fleet
  - $X_{\text{inner-loop}}$ =[<shared vars. header> , <S/C #1 unique vars. > , <S/C #2 unique vars.>, …]
- **Minimum # of Shared Flyby Genes**
  - Encoded in outer-loop header
  - All S/C must share some number of flyby target genes
- **Minimum # of Shared Trajectory Phases**
  - After NULL flybys ignored, remaining identical flyby targets constrained to have identical shared trajectory phases
- **Coordinated Objective: Minimax TOF**

Outer-Loop Multi-Objective Optimizer

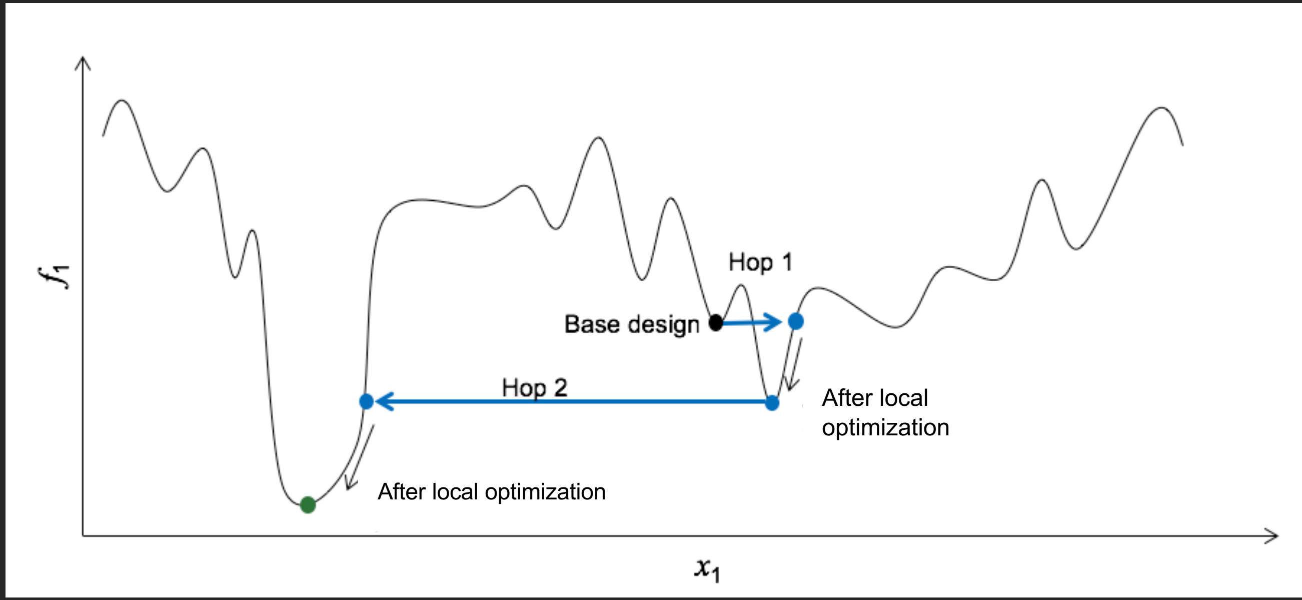
- Non-Dominated Sorting Genetic Algorithm (NSGA-II)
- Finds *Pareto front* spanned by all objectives in multi-objective problem
- Ranking performed by Pareto criterion and crowded tournament selection
- *Cap & Optimize* approach to efficiently optimize multiple objectives for the price of one[3]
  1. Inner-Loop optimizes **one** objective
  2. Outer-loop sets caps on secondary objectives, constraining inner-loop problem
  3. Inner-loop returns solution to outer-loop
  4. Outer-loop extracts secondary objectives' cost & ranks population



Pareto Front concept[13]

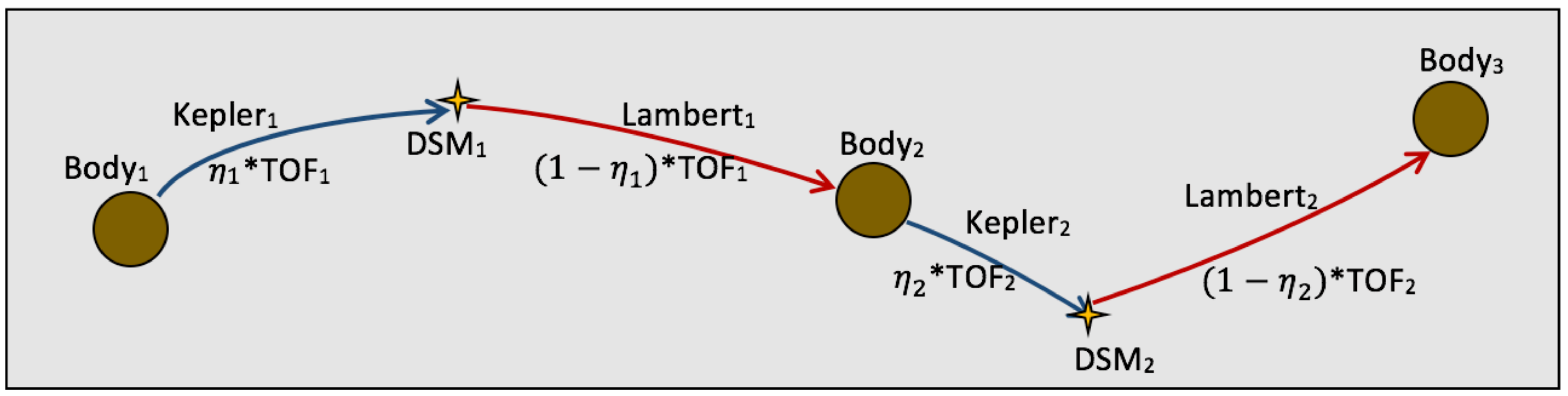
Inner-Loop Global Search Algorithm

- Monotonic Basin Hopping (MBH)
- 4 parameters:
  - Max # global hops
  - Max run time
  - Local hop size
  - Max # local hops
- Not always used with a local optimizer, but addition of local optimizer proved effective



MBH illustration[13]

Trajectory Transcription

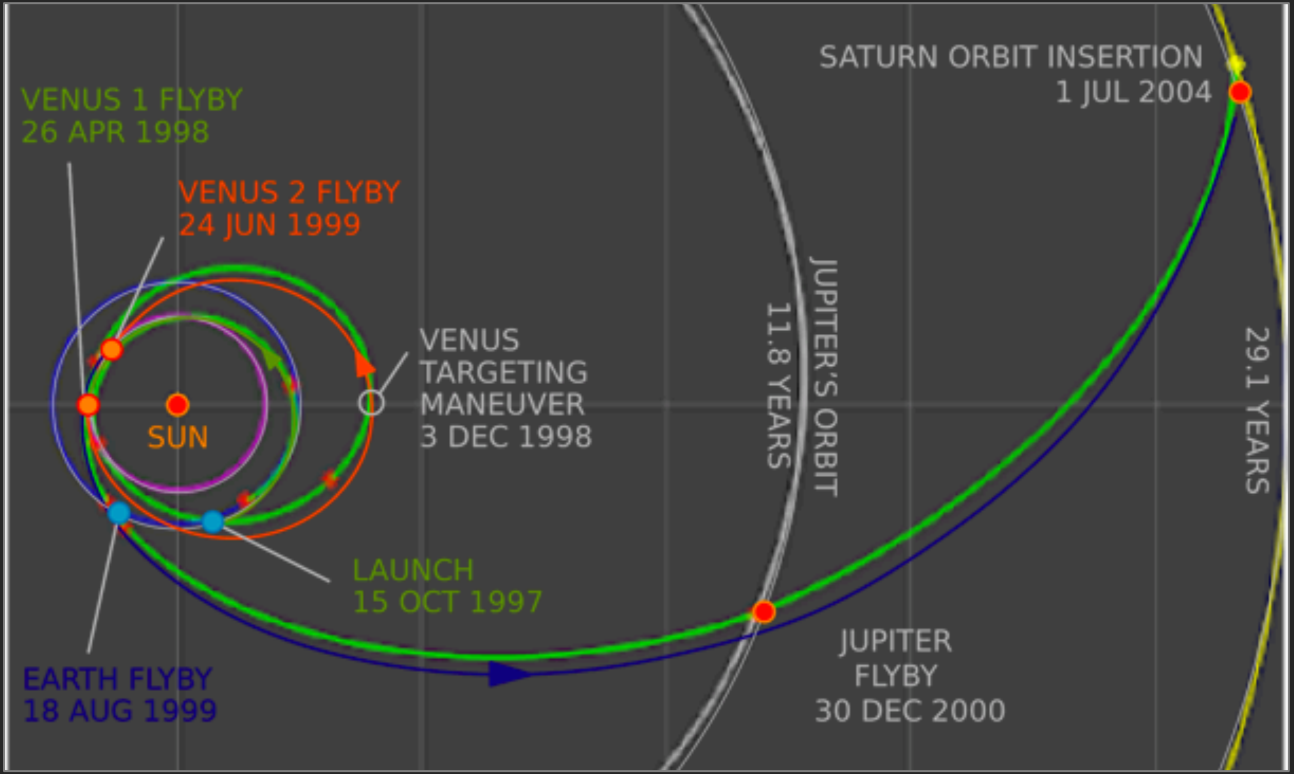


Multiple Gravity Assists with 1 Deep Space Maneuver (MGA1DSM) Transcription illustration developed by Izzo et al. [8]

Reproducing *Cassini's* Cruise with MBH+DE Inner-Loop

DE/best/2/bin Parameter	Value
Population Size	20
Generations	200
Difference Vector Throttle	1.0E-2
Launch Window (days)	90
Mutation Rate	0.05
C_3 bounds (km^2/s^2)	[15, 20]
RLA bounds (degrees)	[0, 360]
DLA bounds (degrees)	[-90, 90]
DSM Index bounds	[0, 1]
β (degrees)	[0, 360]

MBH Parameter	Value
Maximum Global Search Hops	5
Local Hop Magnitude	2.5E-3
Improvement Criterion	1.0E-5
N_{max}	20
Maximum Runtime (minutes)	60



Solution (green) overlaying pre-launch Cassini design. Launch window: 10/1–10/31 1997. Solution used **696 m/s** ΔV v. pre-launch design's 550 m/s. Event dates varied by $\pm$15 days.

Ice Giant Multi-Mission Analysis

- Voyager era conjunction geometry between Uranus & Neptune will not recur until ~2148
- Hughes et al. showed no opportunities for one spacecraft to visit Uranus & Neptune between 2020 – 2070[1]
- 2 options:
  - 2 separate missions
  - 1 dual-spacecraft launch (high risk, nigh infeasible, highest science return)
- Studies
  - Shared launch vehicle only constraint (SHLV)
  - Shared launch vehicle + shared flyby genes constraint (SHFB)
  - Shared launch vehicle + shared trajectory phases constraint (SHTR)

Outer-Loop Parameter	**Value**
Population Size	72
Number of Workers	72
Generations	100
Maximum Intermediate Flyby Targets	5
Mutation Rate	10%
Main Objective	minimize fleet ΔV
Secondary Objective(s)	[minimax TOF]
Launch Window Menu	{[1/1/2030, 5/1/2030] : 4 mo : [9/1/2040, 1/1/2040]}
Global TOF Cap Menu	[10 years : 1 year : 16 years]
Planetary Flyby Menu	[Venus, Earth, Mars, Jupiter, Saturn]
Minimum Shared Flyby Genes Constraint Menu	[0, 1, 2, 3, 4]
Shared Trajectories Constraint (boolean)	[0, 1]
C_3 (km^{2}s^{-2}) Bounds Menu	{[0.0, 2.5] : 2.5 : [22.5, 25.0]}
MBH Parameter	**Value**
Maximum Global Search Hops	10,000
Local Hop Magnitude	$\pm$5% of current decision parameter value
Improvement Criterion	1.0E-5
N_{max}	25
Maximum Runtime (minutes)	60
Outer-Loop Parameter	**Value**
Maximum Intermediate Flyby Targets	**4**
Planetary Flyby Menu	**[Mars, Jupiter, Saturn]**
C_3 (km^{2}s^{-2}) Bounds Menu	**{[25.0, 30.0] : 5.0 : [210.0, 220.0]}**

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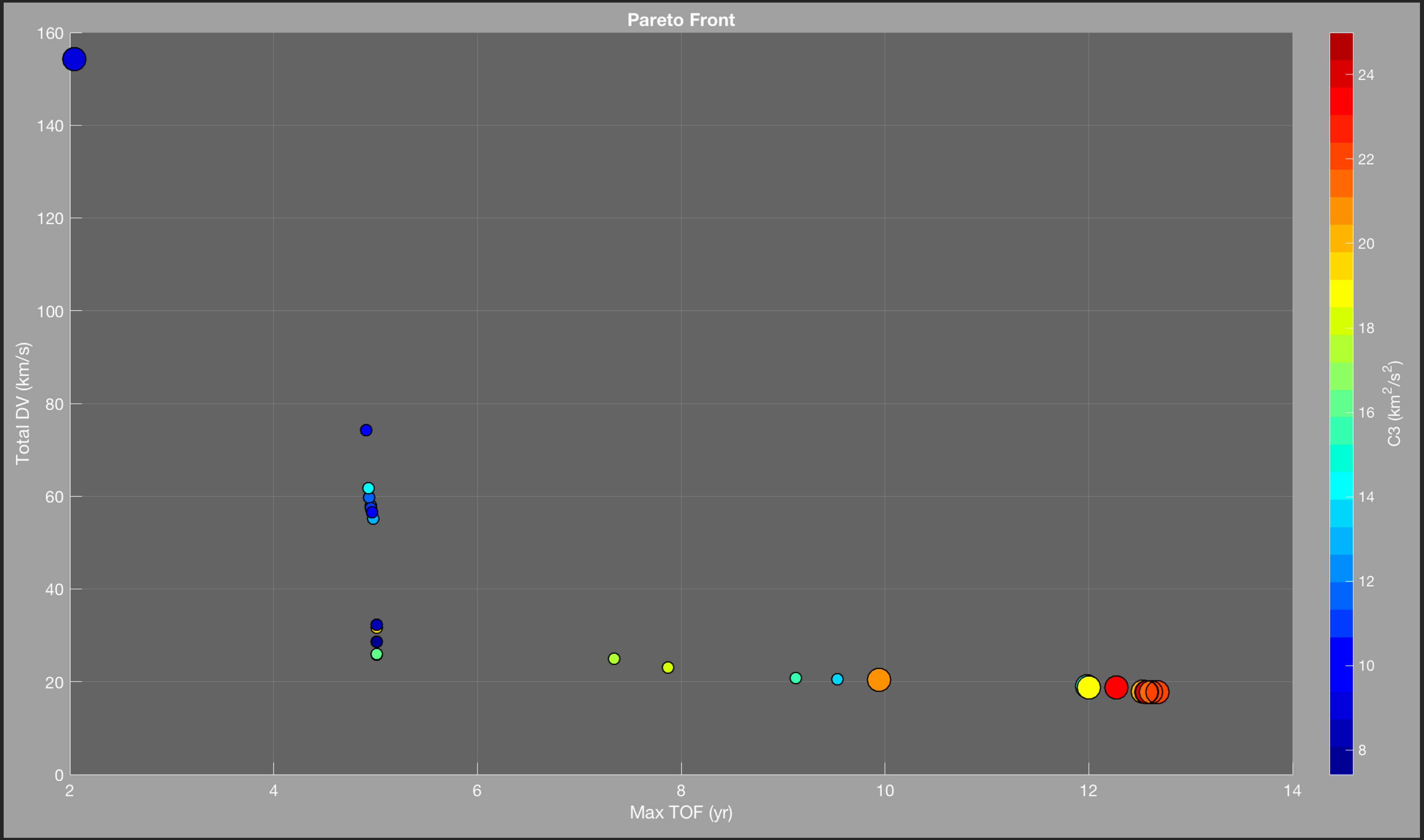
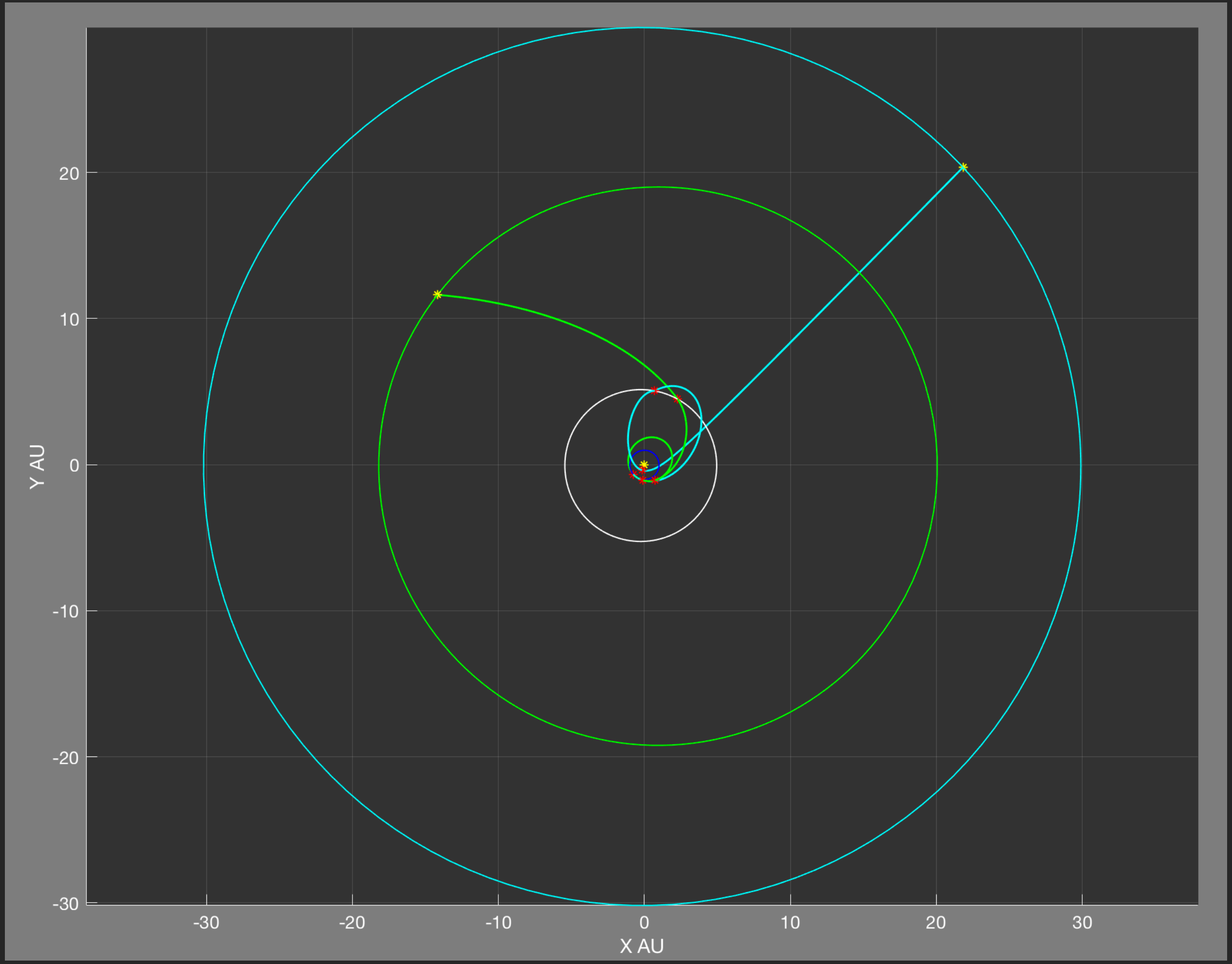
Low C3 SHFB Pareto Front



Marker size: #intermediate flybys

Low C3 SHFB Minimum ΔV Solution

Low C_3, SHFB	Date	C_3 (km^2/s^2)	RLA °	DLA °	ΔV (km/s)	Altitude (r_{planet})
Spacecraft 1	—	—	—	—	—	—
Launch	1 May 2032	25	319.4	4.1	—	—
DSM 1 (km/s)	5 Jul 2034	—	—	—	4.981	—
Flyby Jupiter	24 May 2036	—	—	—	—	50.0
DSM 2 (km/s)	24 May 2036	—	—	—	2.622	—
Encounter Uranus	7 May 2044	—	—	—	—	—
Spacecraft 2	—	—	—	—	—	—
Launch	1 May 2032	25	319.4	4.1	—	—
DSM 1 (km/s)	11 Jun 2032	—	—	—	4.528	—
Flyby Jupiter	27 Dec 2036	—	—	—	—	50.1
DSM 2 (km/s)	1 Mar 2039	—	—	—	5.591	—
Encounter Neptune	1 Jan 2045	—	—	—	—	—



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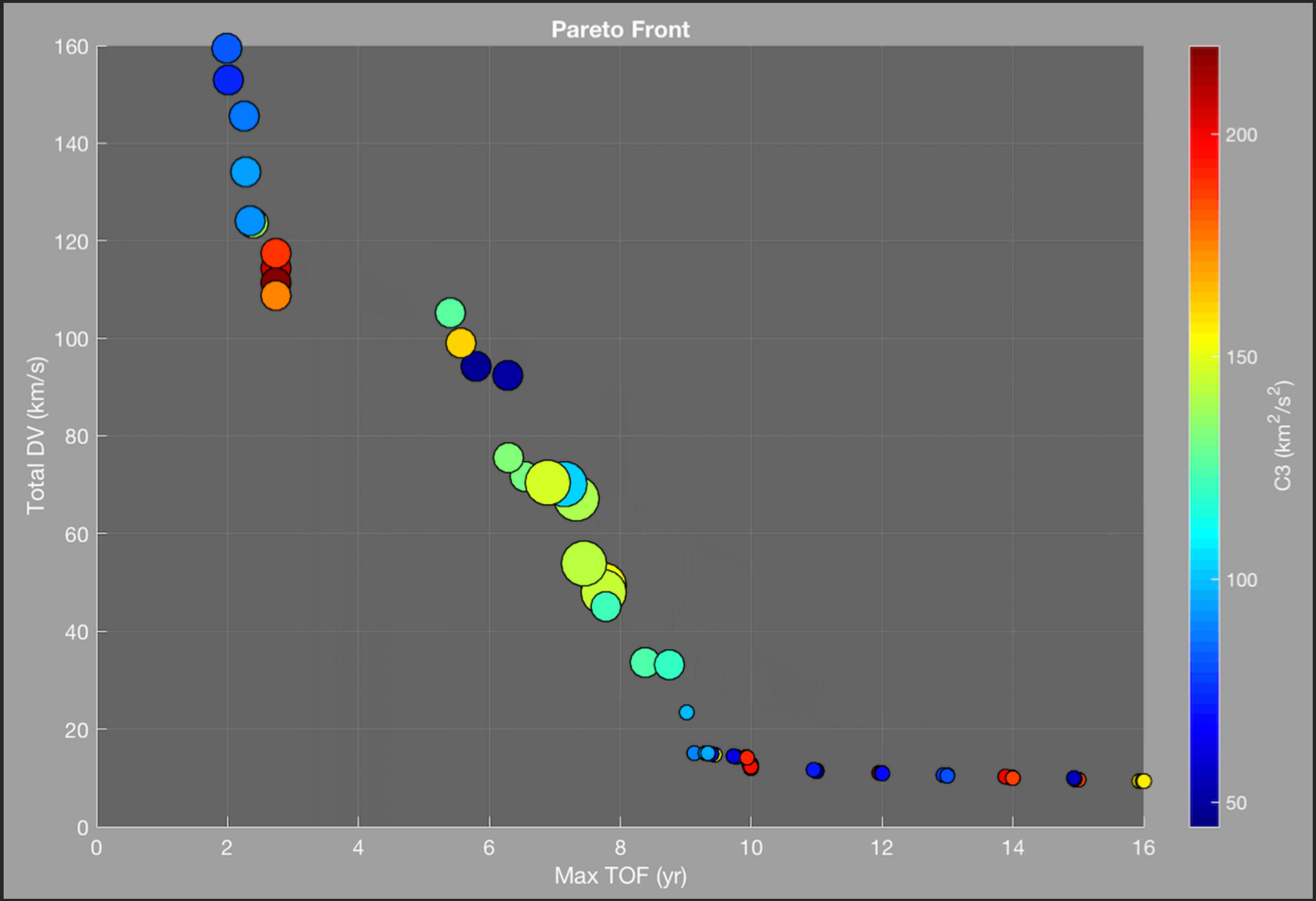
High C3 SHFB Pareto Front



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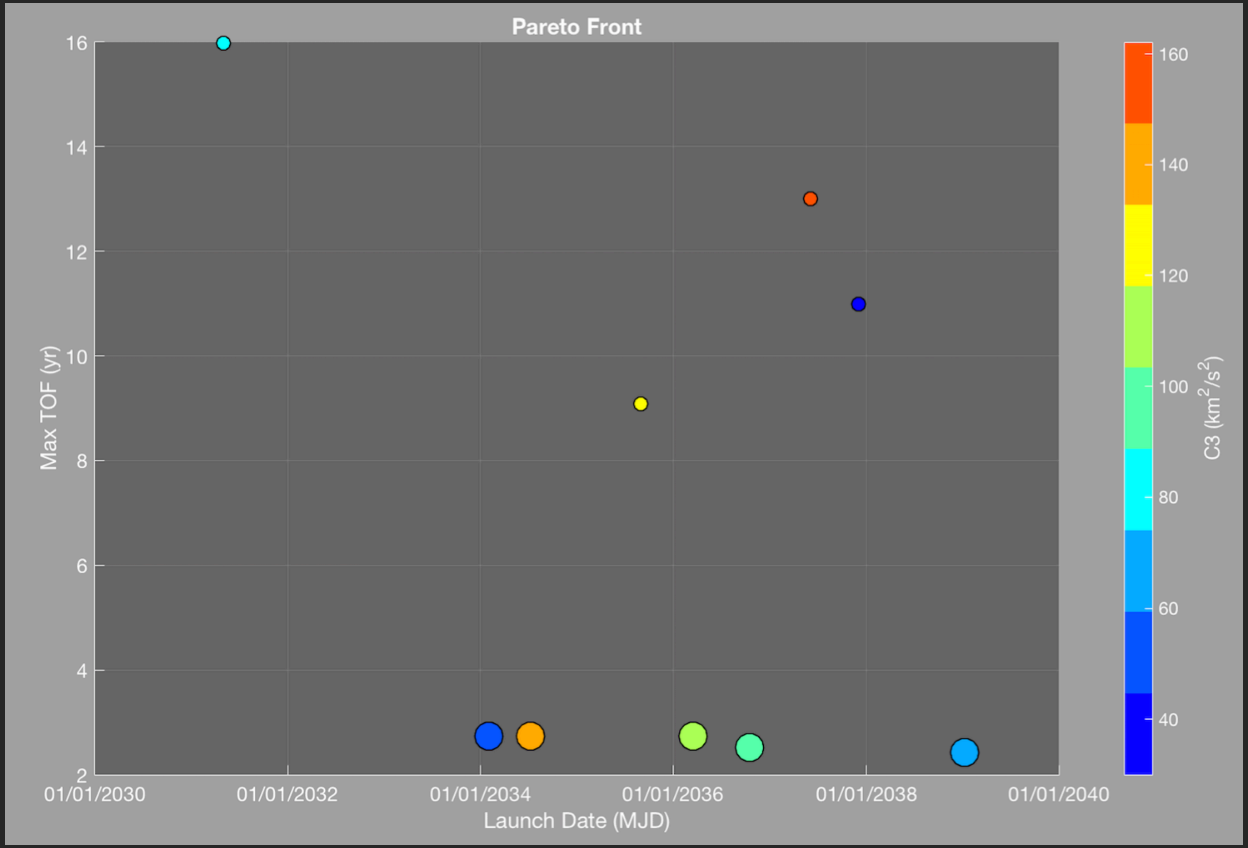
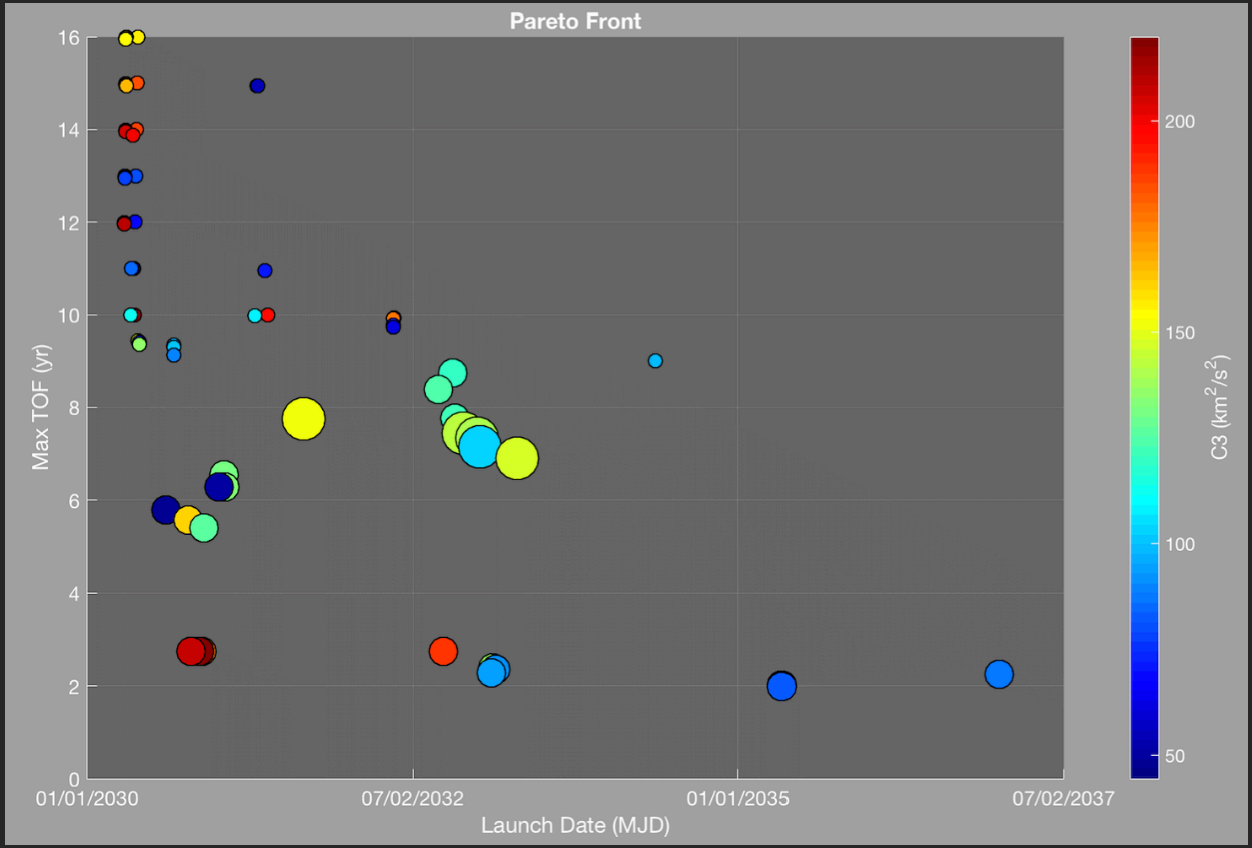
SHFB Pareto Front v. Launch Date

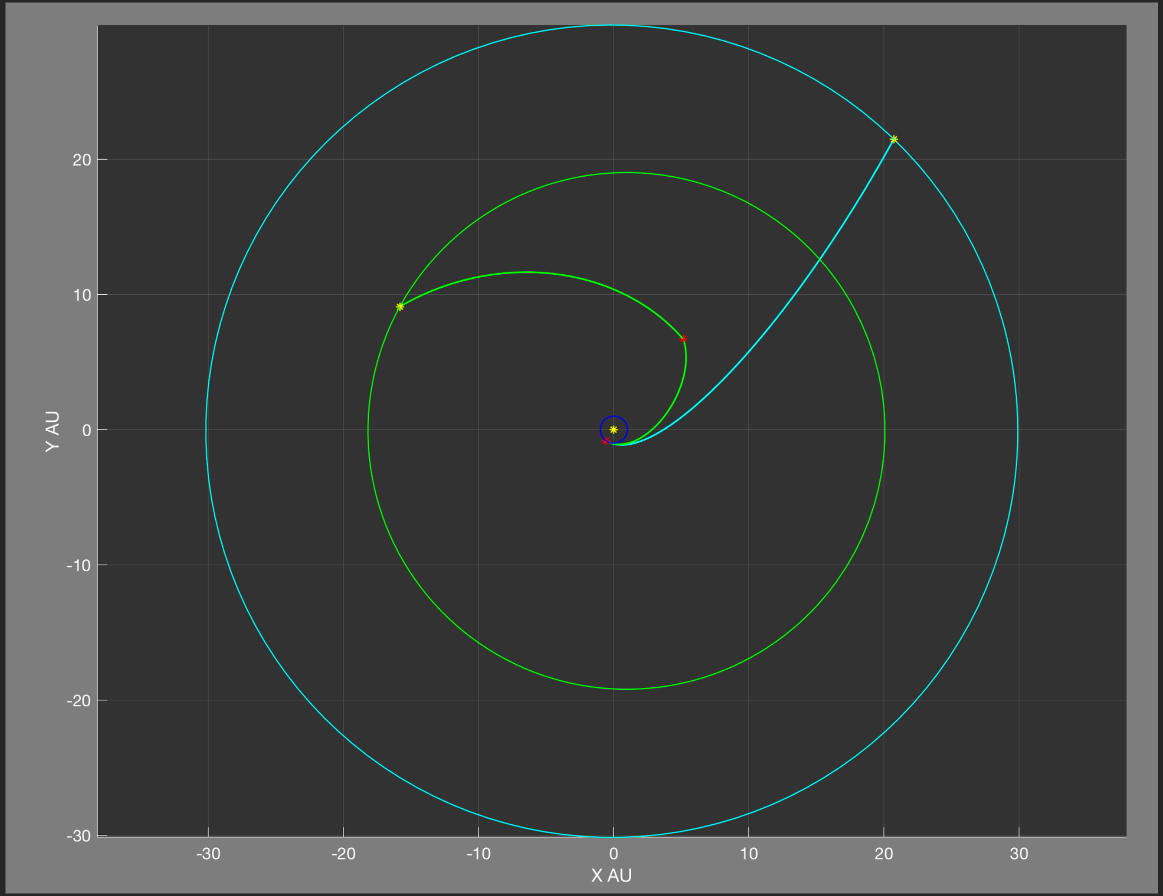




Marker size: #intermediate flybys

High C3 SHFB Minimum ΔV Solution

High C_3, SHFB	Date	C_3 (km^2/s^2)	RLA °	DLA °	ΔV (km/s)	Altitude (r_{planet})
Spacecraft 1	—	—	—	—	—	—
Launch	16 May 2030	150.0	339.3	-37.0	—	—
DSM 1 (km/s)	30 May 2034	—	—	—	7.584	—
Encounter Uranus	16 May 2046	—	—	—	—	—
Spacecraft 2	—	—	—	—	—	—
Launch	16 May 2030	150.0	339.3	-37.0	—	—
DSM 1 (km/s)	16 May 2030	—	—	—	1.854	—
Encounter Neptune	16 May 2046	—	—	—	—	—



Future Work

- Results are promising, but far from optimal
- Needs:
  - More robust, reliable inner-loop
  - Larger outer-loop population size
  - Greater distributed computing resources
- Future work:
  - Address needs
  - Explore new classes of MVMs
  - Explore more coordination constraints & objectives

Acknowledgements

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Appendix

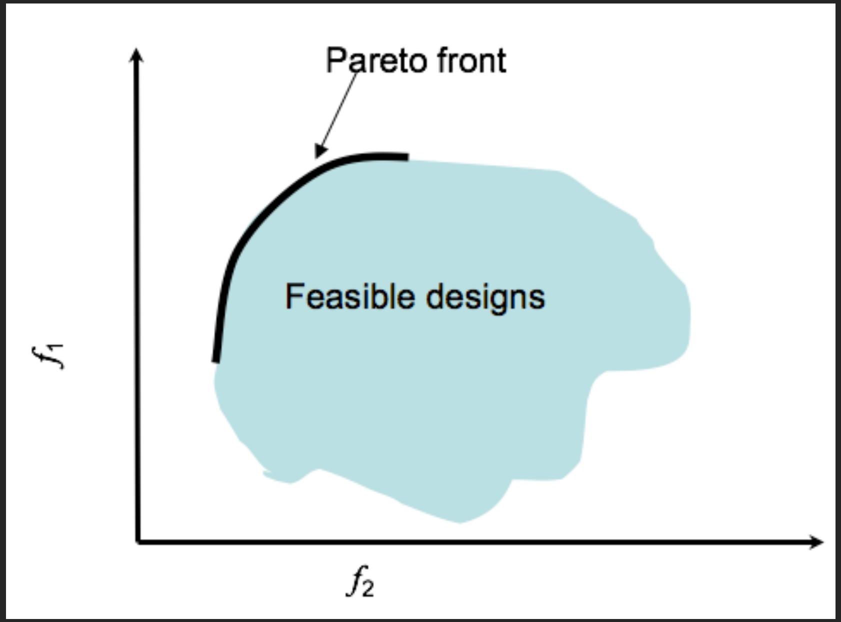
Outer-Loop Multi-Objective Optimizer

- Non-Dominated Sorting Genetic Algorithm (NSGA-II)
- Finds *Pareto front* spanned by all objectives in multi-objective problem
- Ranking:
  - Pareto criterion assigns front rank

    X_i dominates X_j if $\forall f(X_i) \leq f(X_j) \wedge \exists f(X_i) < f(X_j)$
  - Crowded comparison operator maximizes diversity on front

$$r_{cr,i} = \min\left(norm\left(\vec{f}(X_i) - \left(\vec{f}(X_j)\right)\right)\right)$$

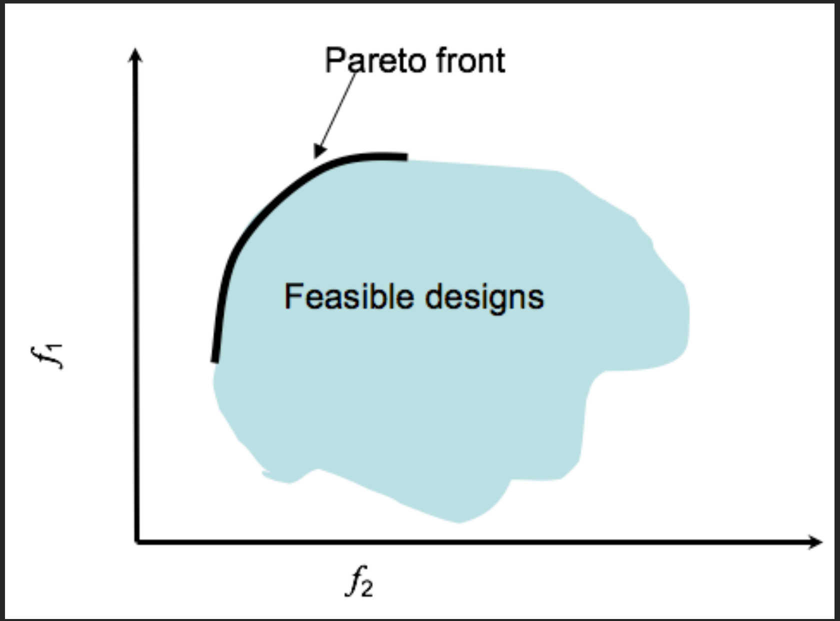
    - Where $\vec{f}$ is the vector of objectives evaluated on a candidate solution X
    - $j \neq i$ and $j = 1{:}N$ members of the front
    - Dominant individuals have longest crowding distance with their nearest neighbors



Pareto Front concept[13]

Outer-Loop Multi-Objective Optimizer

- *Cap & Optimize* approach to efficiently optimize multiple objectives [3]
  - Inner-Loop only optimizes **one** objective (time-consuming)
  - However, solution carries cost info for numerous secondary objectives
  1. Outer-loop sets caps on secondary objectives, constraining the inner-loop problem
  2. Inner-loop returns solution to outer-loop
  3. Outer-loop extracts secondary objectives' cost
  4. Outer-loop performs non-dominated sort & crowded comparison to rank population of candidate solutions
  - Result: *M* objectives for the price of one



Pareto Front concept[13]

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Inner-Loop Local Optimizer

- Version 1: Differential Evolution (DE/best/2/bin) with mutation operator
  - DE/best/2/bin originally used as full inner loop
  - Replaced by MBH, but nesting together proved better performance than either separately
- Version 2: `fmincon()` with mutation enables linear constraints and faster local optimization
- Objective: minimize ΔV of spacecraft fleet
- Constraints:
  - Global TOF, launch window, etc specified by outer-loop

Shared Launch Vehicle Constraint

- Multiple spacecraft constrained to share a launch vehicle
- $[LW_i, C_{3,i}, RLA_i, DLA_i]$ identical for $i = 1,2,\ldots,N$ spacecraft in fleet
- Outer-loop header enforces LW & C_3 bounds genes to be identical
- Genetic crossover constraint forces genes to mate identically
- Inner-loop chooses launch date, C_3, RLA & DLA

  Inner loop vector:

  [<shared param header> , <S/C #1 unique params> , <S/C #2 unique params>, … , <S/C #*N* unique params>]

Minimum # Shared Flyby Genes Constraint

- Voyager spacecraft performed staggered flybys of Jupiter and Saturn to leverage favorable turning angles
- Constraint requiring minimum # of shared flyby genes in outer-loop vector incentivizes exploring different, interesting decision space
- Constraint is encoded in outer-loop header
  - # of minimum shared flyby genes chosen from outer-loop decision menu
  - Genes have 50% chance of being NULL; ignored by inner loop
  - May result in fewer actual duplicate flyby targets than # specified in outer-loop

Minimum # Shared Trajectory Phases Constraint

- Require all S/C in fleet to fly same trajectory for a specific number of flybys
- Can only be switched on if minimum shared flyby genes constraint also on
- Enforced by inner-loop
  - After NULL flybys ignored, remaining identical flyby targets constrained to have identical shared trajectory phases
  - 2D hybrid vector transforms to 1D vector:
  - $X_{inner\ loop}$ = [<shared param header> , <S/C #1 unique params> , <S/C #2 unique params>, … , <S/C #*N* unique params>]

Coordination Objective Approach

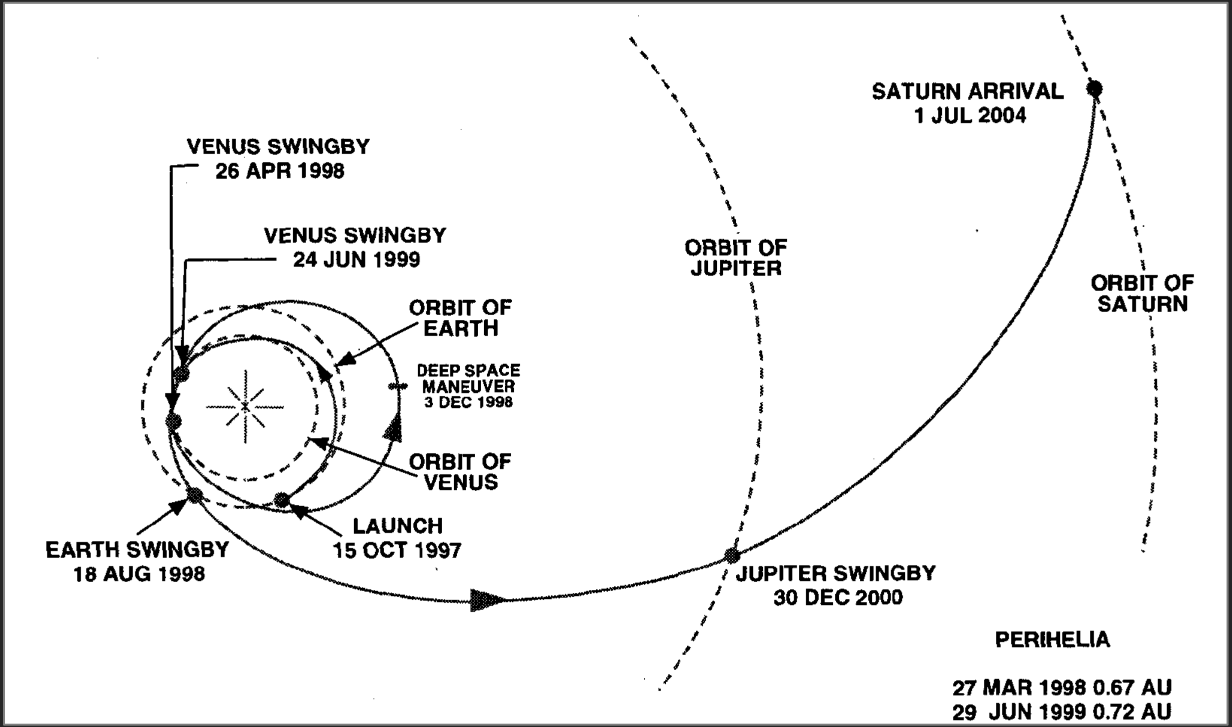
- How to couple cost of each S/C?
- Minimax approach in outer-loop, *i.e.*, “weakest link”
- Example: TOF cost for entire fleet = max TOF w/in fleet
- Result: each S/C in fleet forced to reduce TOF
- Can be applied to any number of outer-loop objectives
- Effective approach in integer genetic algorithms
- Separate challenge to implement for gradient-based optimizer

Reproducing *Cassini's* Cruise

- Test of MBH+DE inner-loop
- Launch window: Oct 1 – Oct 31 1997
- TOF phases bounded ±10 days from nominal Cassini phase TOF
- No initial guess provided

DE/best/2/bin Parameter	Value
Population Size	20
Generations	200
Difference Vector Throttle	1.0E-2
Launch Window (days)	90
Mutation Rate	0.05
C_3 bounds (km^2/s^2)	[15, 20]
RLA bounds (degrees)	[0, 360]
DLA bounds (degrees)	[-90, 90]
DSM Index bounds	[0, 1]
β (degrees)	[0, 360]

MBH Parameter	Value
Maximum Global Search Hops	5
Local Hop Magnitude	2.5E-3
Improvement Criterion	1.0E-5
N_{max}	20
Maximum Runtime (minutes)	60



Cassini pre-launch nominal design[14]

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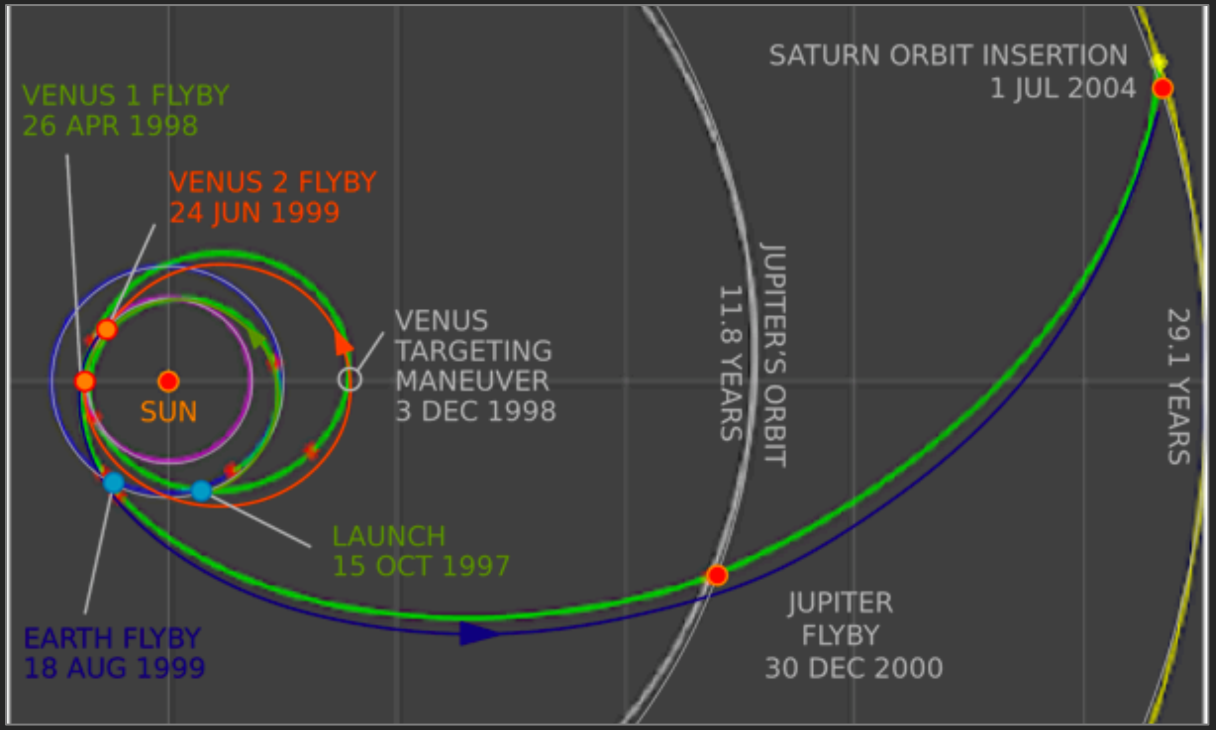
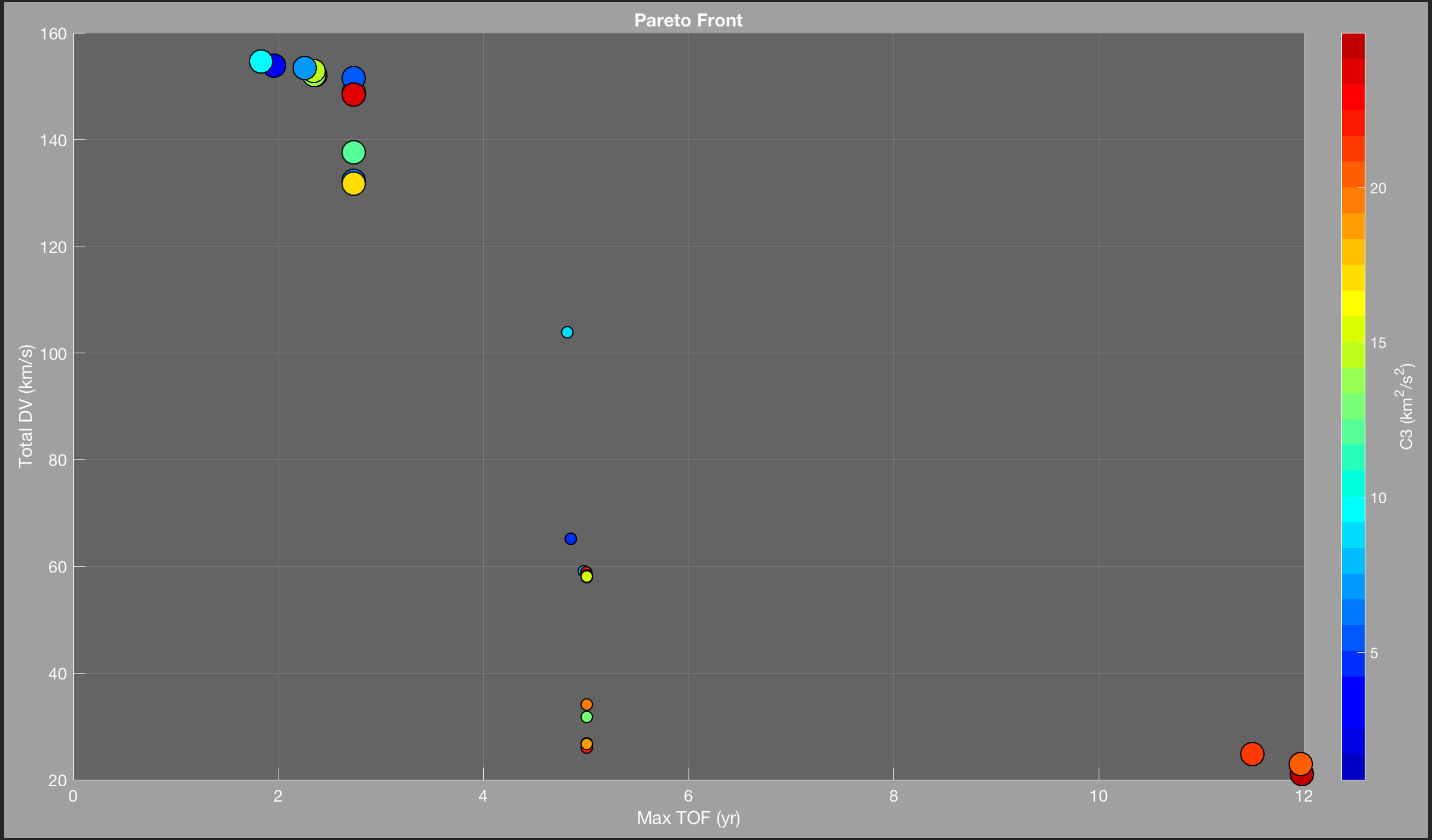
Reproducing *Cassini's* Cruise

- Cassini-like solution used 696 m/s ΔV versus pre-launch design of 550 m/s
- Launch, flyby, and encounter dates varied by ± 15 days
- Longer run time may marginally improve solution, as might multiple separate inner-loop runs, but reliability is ultimately tuning problem



Inner-loop solution (green) overlaying pre-launch Cassini design

Low C3 SHTR Pareto Front (no near-feasible solutions)



Marker size: #intermediate flybys

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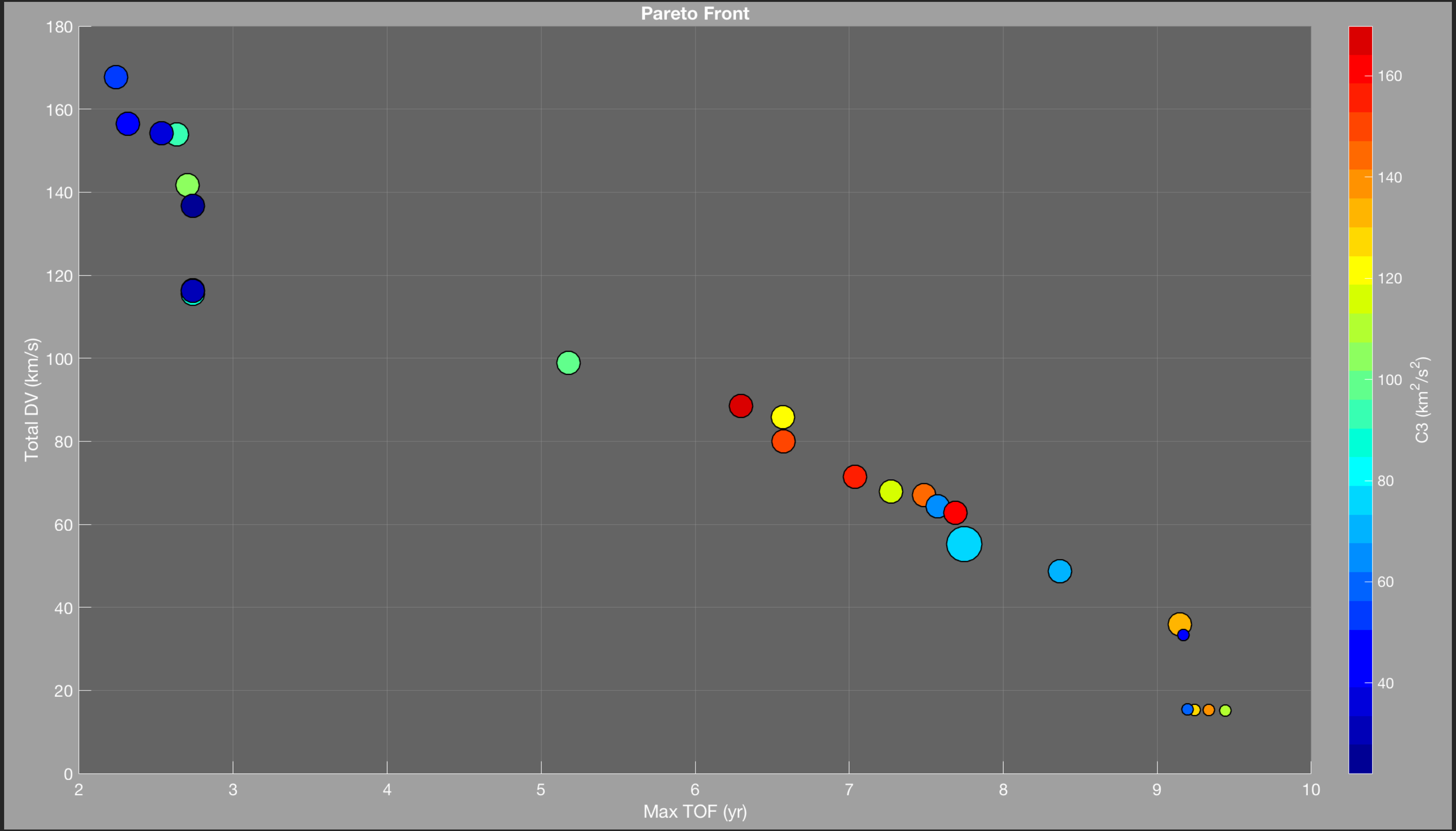
High C3 SHLV Pareto Front



Marker size: #intermediate flybys

High C3 SHLV Minimum ΔV Solution

High C_3, SHLV	**Date**	**C_3 (km^2/s^2)**	**RLA °**	**DLA °**	**ΔV (km/s)**	**Altitude (r_{planet})**
Spacecraft 1	—	—	—	—	—	—
Launch	8 Jun 2030	121.2	40.4	-5.2	—	—
DSM 1 (km/s)	8 Sep 2030	—	—	—	4.546	—
Encounter Uranus	17 Nov 2039	—	—	—	—	—
Spacecraft 2	—	—	—	—	—	—
Launch	8 Jun 2030	121.2	40.4	-5.2	—	—
DSM 1 (km/s)	13 Dec 2033	—	—	—	10.596	—
Flyby Jupiter	12 Oct 2034	—	—	—	—	93.9
DSM 2 (km/s)	20 Oct 2035	—	—	—	0.047	—
Encounter Neptune	9 Oct 2039	—	—	—	—	—