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REFINING LUCY MISSION DELTA-V DURING SPACECRAFT DESIGN USING TRAJECTORY OPTIMIZATION WITHIN HIGH-FIDELITY MONTE CARLO MANEUVER ANALYSIS

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Recent advances linking medium-fidelity trajectory optimization and high-fidelity trajectory propagation/maneuver design software with Monte Carlo maneuver analysis and parallel processing enabled realistic statistical delta-V estimation well before launch. Completing this high-confidence, refined statistical maneuver analysis early enabled release of excess delta-V margin for increased dry mass margin for the Lucy Jupiter Trojan flyby mission. By 3.3 years before launch, 16 of 34 TCMs had 1000 re-optimized trajectory design samples, yielding tens of m/s lower 99%-probability delta-V versus targeting maneuvers to one optimal trajectory. One year later, 1000 re-optimized samples of all deterministic maneuvers and subsequent flybys further lowered estimated delta-V.

INTRODUCTION

The NASA Discovery Program's Lucy mission, which plans to launch in late 2021, will utilize an 11.4-year trajectory that lowers launch energy and delta-V (ΔV, also known as velocity change) requirements by using three Earth gravity-assist flybys to target a mainbelt asteroid flyby and five flybys of six compositionally diverse Jupiter Trojan asteroids. These Trojan flybys will occur near Jupiter's distance from the Sun in both the L4 and L5 spatial regions about 60º ahead of and 60º behind Jupiter's orbital location.

Recent advances linking medium-fidelity global trajectory optimization and high-fidelity trajectory propagation/maneuver design software with Monte Carlo maneuver analysis and parallel processing have enabled more realistic statistical ΔV estimation well before launch. Completion of this high-confidence, refined statistical maneuver analysis occurred early enough to justify releasing excess ΔV margin for increased dry mass margin for the Lucy mission. Flybys of two Trojan asteroids less than five weeks apart created a nearly 70-m/s increase in statistical ΔV that was concentrated in a maneuver shortly after the first of these two flybys. This 70 m/s ΔV "penalty" motivated the introduction of trajectory re-optimization into the Monte Carlo analysis process enabling small changes in the epochs and geometry of the remaining Trojan encounters and deterministic maneuvers. This paper will briefly discuss the process used for the interface between the trajectory optimization, trajectory propagation\maneuver design with realistic error modeling and

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Monte Carlo analysis software. The computation-intensive characteristics of this complex trajectory optimization and statistical maneuver analysis process is feasible due to efficient use of parallel processing and recent software advances.

This paper will discuss results from Lucy mission flight dynamics[1] engineers who have developed and applied interfaces between: 1) rapid-convergence, medium-fidelity trajectory optimization software with Monte Carlo capability, 2) slower-convergence, high-fidelity software that targets maneuvers and 3) Monte Carlo analysis software. This trajectory optimization was originally performed using STK (Systems Tool Kit) at Lockheed Martin Space. Trajectory optimization is now more rapidly and optimally performed using NASA Goddard Space Flight Center's medium-fidelity EMTG (Evolutionary Mission Trajectory Generator) software[2,3], with EMTG producing target epochs and spacecraft states (including mass) for 1000 perturbed cases. These data are provided to the MIRAGE (Multiple Interferometric Ranging Analysis using GPS Ensemble) flight-qualified software suite for maneuver design and trajectory propagation using operationally accurate force and maneuver execution error models.

The EMTG software uses monotonic basin-hopping for global optimization. A Python wrapper named PEATSA[4] can be used to automate EMTG execution to conduct trade studies and conduct Monte Carlo analyses with reduced analyst oversight. When used in conjunction with a high-performance computer, EMTG can take advantage of parallel processing to make possible rapid optimization of a large number of complex trajectories.

The MIRAGE software suite, JPL-developed software licensed to KinetX for use on NASA-approved mission support, is used by KinetX-developed software called MONSTER (Monte-Carlo Operational Navigation Simulation for Trajectory Evaluation and Research) and PIRATE (PVdrive Interface and Robust Astrodynamic Targeting Engine) to apply high-fidelity force models and maneuver execution errors to EMTG Monte Carlo re-optimized results. The KinetX-developed PIRATE software links the MIRAGE propagation engine to the high-performance numerical optimization package Sparse Nonlinear Optimizer (SNOPT)[5]. Post-processing the results into a realistic probabilistic maneuver analysis helps to set a conservative, yet accurate, ΔV budget.

LUCY TRAJECTORY DESIGN OVERVIEW

Providing a chronological and quantitative perspective of the Lucy mission's four operational phases is helpful to provide the context for solar system body encounters and the TCMs (Trajectory Correction Maneuvers) and larger DSMs (Deep Space Maneuvers) discussed in this paper. Launch phase will begin at Cape Canaveral in Florida with a characteristic energy (C3) that will not exceed 29.2 km^2/s^2 and will extend until 30 days after launch at TCM 1. Initial Cruise phase continues through DSM 1 and the first Earth gravity-assist (EGA) flyby one year after launch, then DSM 2 will target the second EGA flyby 3.1 years after launch and then the flyby of main-belt asteroid Donaldjohanson in April 2025. After completing this asteroid flyby rehearsal, DSM 3 will set up the L4 Trojan Flyby phase by targeting the Jupiter Trojan Eurybates encounter in August 2027 and the Trojan Polymele encounter just 34 days later. The L4 Trojan Flyby phase will conclude with DSMs 4 and 5 targeting Trojans Leucus and Orus, respectively, in April 2028 and November 2028. The final nominal mission segment, the Late Cruise and L5 Trojan Flyby phase, will include a third EGA flyby in December 2030 that, along with the earlier DSM 5, will target a flyby of Jupiter Trojan binary Patroclus and Menoetius in March 2033.

The current TCM schedule has a conservative strategy that minimizes risk through 33 primary maneuver opportunities, 1 pre-EGA near-Earth object collision avoidance contingency maneuver per flyby, 1 secondary cleanup TCM after each post-EGA cleanup TCM, and 12 pre-asteroid encounter contingency TCM placeholders (2 per flyby). Tables 1 and 2 identify the timing of all

TCMs and the corresponding events that each TCM will target for the launch period open and close. The strategy for placement of statistical TCMs includes 30 and 10 days before each EGA and 30 and 7 days before each asteroid encounter. Because the L4 Trojan Eurybates and Polymele encounters are only 34 days apart, the second-to-last targeting TCM will be 27 days before the Polymele flyby. The contingency TCM option one day before each EGA is there to alter EGA timing to avoid a spacecraft collision.

Table 1. Schedule of Course-Correction Maneuvers for Lucy Launch Period Day 1

Event / Milestone	Epoch	Event / Milestone	Epoch
Launch to EGA 1		Post-Eurybates to Polymele	
Launch	**Oct 16, 2021**	TCM 22*	Aug 18-20, 2027
TCM 1	Nov 15, 2021	TCM 23	Sep 8, 2027
TCM 2	Dec 30, 2021	TCM 23a (E-6d Contingency)	Sep 9, 2027
DSM 1 (TCM 3)*	May 23 – Jun 8, 2022	TCM 23b (E-5d Contingency)	Sep 10, 2027
TCM 4*	Jun 13-29, 2022	**Polymele Encounter**	**Sep 15, 2027**
TCM 5	Sep 16, 2022	Post-Polymele to Leucus	
TCM 6	Oct 6, 2022	DSM 4 (TCM 24)*	Sep 29 – Oct 11, 2027
TCM 6a (CA contingency)	Oct 15, 2022	TCM 25*	Oct 20 – Nov 1, 2027
EGA 1	**Oct 16, 2022**	TCM 26	Mar 19, 2028
Post-EGA 1 to EGA 2		TCM 27	Apr 11, 2028
TCM 7	Oct 26, 2022	TCM 27a (E-6d Contingency)	Apr 12, 2028
TCM 8	Nov 15, 2022	TCM 27b (E-5d Contingency)	Apr 13, 2028
DSM 2 (TCM 9)*	Feb 1-7, 2024	**Leucus Encounter**	**Apr 18, 2028**
TCM 10*	Feb 22-28, 2024	Post-Leucus to Orus	
TCM 11	Nov 13, 2024	TCM 28	May 18, 2028
TCM 12	Dec 3, 2024	DSM 5 (TCM 29)*	Jul 16 - Jul 31, 2028
TCM 12a (CA contingency)	Dec 12, 2024	TCM 30*	Aug 6 - Aug 21, 2028
EGA 2	**Dec 13, 2024**	TCM 31	Oct 12, 2028
Post-EGA 2 to Donaldjohanson		TCM 32	Nov 4, 2028
TCM 13	Dec 23, 2024	TCM 32a (E-6d Contingency)	Nov 5, 2028
TCM 14	Jan 12, 2025	TCM 32b (E-5d Contingency)	Nov 6, 2028
TCM 15	Mar 21, 2025	**Orus Encounter**	**Nov 11, 2028**
TCM 16	Apr 13, 2025	Post-Orus to EGA 3	
TCM 16a (E-6d Contingency)	Apr 14, 2025	TCM 33	Jan 7, 2029
TCM 16b (E-5d Contingency)	Apr 15, 2025	TCM 34	Nov 26, 2030
Donaldjohanson Encounter	**Apr 20, 2025**	TCM 35	Dec 16, 2030
Post-Donaldjohanson to Eurybates		TCM 35a (CA contingency)	Dec 25, 2030
TCM 17	May 20, 2025	**EGA 3**	**Dec 26, 2030**
DSM 3 (TCM 18)*	Mar 6 – May 3, 2027	Post-EGA 3 to Patroclus-Menoetius (PM)	
TCM 19*	Apr 10 – Jun 14, 2027	TCM 36	Jan 5, 2031
TCM 20	Jul 13, 2027	TCM 37	Jan 25, 2031
TCM 21	Aug 5, 2027	TCM 38	Jan 31, 2033
TCM 21a (E-6d Contingency)	Aug 6, 2027	TCM 39	Feb 23, 2033
TCM 21b (E-5d Contingency)	Aug 7, 2027	TCM 39a (E-6d Contingency)	Feb 24, 2033
Eurybates Encounter	**Aug 12, 2027**	TCM 39b (E-5d Contingency)	Feb 25, 2033
(First Trojan Encounter)		**PM Binary Encounter**	**Mar 2, 2033**

* Exact dates to be selected in flight well in advance, after prior maneuver reconstruction and trajectory re-optimization.

After launch vehicle separation, the first use of the propulsion system for a trajectory modification will occur during the execution of TCM 1 at 30 days after launch. The spacecraft will coast on a ballistic cruise trajectory until about six months after launch when DSM 1 will target the first Earth gravity assist (EGA 1) one year after launch. The velocity change (ΔV) for DSM 1 is small for the first half of the 21-day launch period, which makes it practical to be executed using the

TCM thrusters. For launch dates near the close of the launch period, the DSM 1 ΔV is large enough that execution will occur using the bipropellant main engine. An initial target offset and a series of walk-in maneuvers will be performed in the months before EGA 1 to ensure the spacecraft is never on an Earth intercept trajectory. This strategy is currently in place for each of the three EGAs such that, with all predicted errors and trajectory perturbations accounted for, the probability of coming within 125 km of Earth's surface (atmospheric entry approximation) stays less than 1% (current requirement with analyses in this report using the older 0.5% requirement) if no subsequent maneuvers can be performed. The minimum target altitude for EGA 1 ranges from 300 km to 2390 km across the launch period.

Table 2. Schedule of Course-Correction Maneuvers for Lucy Launch Period Day 21

Event / Milestone	Epoch	Event / Milestone	Epoch
Launch to EGA 1		***Post-Eurybates to Polymele***	
Launch	**Nov 5, 2021**	*TCM 22**	*Aug 18-20, 2027*
TCM 1	*Dec 5, 2021*	*TCM 23*	*Sep 8, 2027*
TCM 2	*Jan 19, 2022*	*TCM 23a (E-6d Contingency)*	*Sep 9, 2027*
DSM 1 (TCM 3)	*Jul 29, 2022*	*TCM 23b (E-5d Contingency)*	*Sep 10, 2027*
TCM 4	*Aug 12, 2022*	**Polymele Encounter**	**Sep 15, 2027**
TCM 5	*Oct 1, 2022*	***Post-Polymele to Leucus***	
TCM 6	*Oct 21, 2022*	*DSM 4 (TCM 24)**	*Sep 28 – Oct 7, 2027*
TCM 6a (CA contingency)	*Oct 30, 2022*	*TCM 25**	*Oct 19 – Oct 28, 2027*
EGA 1	**Oct 31, 2022**	*TCM 26*	*Mar 19, 2028*
Post-EGA 1 to EGA 2		*TCM 27*	*Apr 11, 2028*
TCM 7	*Nov 10, 2022*	*TCM 27a (E-6d Contingency)*	*Apr 12, 2028*
TCM 8	*Nov 30, 2022*	*TCM 27b (E-5d Contingency)*	*Apr 13, 2028*
DSM 2 (TCM 9)	*Sep 24, 2023*	**Leucus Encounter**	**Apr 18, 2028**
TCM 10	*Oct 8, 2023*	***Post-Leucus to Orus***	
TCM 11	*Nov 13, 2024*	*TCM 28*	*May 18, 2028*
TCM 12	*Dec 3, 2024*	*DSM 5 (TCM 29)**	*Jul 18 - Jul 29, 2028*
TCM 12a (CA contingency)	*Dec 12, 2024*	*TCM 30**	*Aug 8 - Aug 19, 2028*
EGA 2	**Dec 13, 2024**	*TCM 31*	*Oct 12, 2028*
Post-EGA 2 to Donaldjohanson		*TCM 32*	*Nov 4, 2028*
TCM 13	*Dec 23, 2024*	*TCM 32a (E-6d Contingency)*	*Nov 5, 2028*
TCM 14	*Jan 12, 2025*	*TCM 32b (E-5d Contingency)*	*Nov 6, 2028*
TCM 15	*Mar 21, 2025*	**Orus Encounter**	**Nov 11, 2028**
TCM 16	*Apr 13, 2025*	***Post-Orus to EGA 3***	
TCM 16a (E-6d Contingency)	*Apr 14, 2025*	*TCM 33*	*Jan 7, 2029*
TCM 16b (E-5d Contingency)	*Apr 15, 2025*	*TCM 34*	*Nov 26, 2030*
Donaldjohanson Encounter	**Apr 20, 2025**	*TCM 35*	*Dec 16, 2030*
Post-Donaldjohanson to Eurybates		*TCM 35a (CA contingency)*	*Dec 25, 2030*
TCM 17	*May 20, 2025*	**EGA 3**	**Dec 26, 2030**
*DSM 3 (TCM 18)**	*Mar 4 – May 3, 2027*	***Post-EGA 3 to Patroclus-Menoetius (PM)***	
*TCM 19**	*Apr 22 – Jun 14, 2027*	*TCM 36*	*Jan 5, 2031*
TCM 20	*Jul 13, 2027*	*TCM 37*	*Jan 25, 2031*
TCM 21	*Aug 5, 2027*	*TCM 38*	*Feb 2, 2033*
TCM 21a (E-6d Contingency)	*Aug 6, 2027*	*TCM 39*	*Feb 25, 2033*
TCM 21b (E-5d Contingency)	*Aug 7, 2027*	*TCM 39a (E-6d Contingency)*	*Feb 26, 2033*
Eurybates Encounter	**Aug 12, 2027**	*TCM 39b (E-5d Contingency)*	*Feb 27, 2033*
(First Trojan Encounter)		**PM Binary Encounter**	**Mar 4, 2033**

* Exact dates to be selected in flight well in advance, after prior maneuver reconstruction and trajectory re-optimization.

Earth Gravity Assist 1 will increase Lucy's heliocentric orbit period to about two years with a return to Earth on December 13, 2024. This orbit requires DSM 2 to target EGA 2 perigee conditions, including a 344- to 576-km perigee altitude (with appropriate offset until TCMs walk in the aim point as mentioned above), to set up an 800-km flyby of main belt asteroid Donaldjohanson on April 20, 2025. The primary purpose of EGA 2 is to increase Lucy's heliocentric orbit period from 2 years to 6 years, thereby propelling the spacecraft to an aphelion near Jupiter's orbit distance where the L4 Trojans will be.

Two years after encountering Donaldjohanson, Lucy will execute DSM 3 around April 3, 2027 to target Jupiter Trojan asteroid Eurybates on August 12, 2027. Lucy will fly past Eurybates at 5.78 km/s, 5.67 AU from the Sun, with an 81° approach solar phase angle. Close approach at Eurybates will be targeted to 1000 km from Eurybates through the subsolar point.

After the Eurybates encounter, only two small statistical maneuvers are planned to encounter Jupiter Trojan asteroid Polymele on September 15, 2027. Lucy will fly past Polymele at 6.02 km/s, 5.71 AU from the Sun, with an 82° approach solar phase angle. Statistical TCMs executed 27 days and 7 days prior to encounter will refine the encounter delivery accuracy enough to satisfy science goals for the 399-km range Polymele encounter through the subsolar point.

Two weeks after the Polymele encounter, Lucy will perform DSM 4 in late September or early October of 2027 to target Jupiter Trojan asteroid Leucus on April 18, 2028. Lucy will fly past Leucus at 5.87 km/s, 5.67 AU from the Sun, with a 104° approach solar phase angle. Two statistical TCMs 30 days and 7 days before the encounter will refine the encounter delivery accuracy. Close approach at Leucus will be targeted to 1000 km through the subsolar point.

Three months after the Leucus encounter, Lucy will perform DSM 5 in mid-to-late July 2028 to target Jupiter Trojan asteroid Orus on November 11, 2028, followed by EGA3 and the L5 mission phase. Lucy will fly past Orus at 7.14 km/s, 5.33 AU from the Sun, with a 126° approach solar phase angle. As with most other encounters. Two statistical TCMs located 30 days and 7 days before the encounter will refine the encounter delivery accuracy. Close approach at Orus will be targeted to 1000 km through the subsolar point. Statistical maneuvers will be required to refine the EGA3 flyby.

Lucy will use a 626-km nominal-altitude Earth flyby on December 26, 2031, increasing heliocentric orbit inclination by 9° to target Jupiter Trojan asteroids Patroclus and Menoetius. Lucy will fly past the Jupiter Trojan binary Patroclus and Menoetius on March 2, 2033 at 8.8 km/s, 5.4 AU from the Sun, with an 18° solar phase angle.

STATISTICAL MANEUVER ANALYSIS USING PARTIAL TRAJECTORY RE-OPTIMIZATION

Early Lucy mission propellant estimation used the long-established practice of defining a planetary mission's ΔV budget based on a Monte Carlo statistical maneuver analysis of a large number of sample trajectories with each maneuver designed to return the spacecraft from a perturbed position to an optimized reference trajectory. Modeled trajectory perturbation sources include maneuver execution error models (see Table 3), knowledge errors in spacecraft ephemerides, and small force model uncertainty such as solar radiation pressure acting on sunlit spacecraft surface areas corresponding to predicted spacecraft Sun-relative orientations. Trajectory "re-optimization" refers to the practice of beginning the preliminary or final design of every deterministic TCM with a new minimum propellant usage redesign of the complete future spacecraft trajectory including all future deterministic maneuvers and every closest approach location and epoch at Earth or asteroid flybys. This trajectory re-optimization is currently performed for all 1000 sample trajectories using the

NASA GSFC's EMTG software, with EMTG produced target spacecraft states and epochs provided to MIRAGE-based software for propagation using flight-fidelity trajectory perturbation models.

Table 3. Main and TCM Engine Maneuver Execution Errors (3-sigma)

Main Engine Maneuver Magnitude Error (ΔV >100 m/s)	+/- 1%
Main Engine Maneuver Magnitude Error (100 m/s > ΔV >50 m/s)	+/- 2%
Main Engine Maneuver Transverse Error (ΔV >100 m/s)	+/- 2%
Main Engine Maneuver Transverse Error (100 m/s > ΔV >50 m/s)	+/- 4%

TCM Magnitude Error	RSS (0.02 m/s, 2% of ΔV magnitude)
TCM Transverse Error (ΔV >10 m/s)	0.03 m/s + 2% of ΔV magnitude, total
TCM Transverse Error (ΔV < 10 m/s)	0.03 m/s + 4% of ΔV magnitude, total

Table 4. Launch Open Mission ΔV Usage *without* Re-optimization (m/s)

TCM	Purpose/Timing	Nominal Epoch	Deterministic	Mean	Std. Dev.	95%	99%	Target Bias
1	Injection Correction	15-Nov-2021	0.010	4.263	1.888	7.656	9.234	none
2	DSM-1 (TCM)	19-Apr-2022	13.224	13.383	0.618	14.405	14.858	2 X radial
3	DSM-1 Cleanup	03-May-2022	0.831	0.848	0.069	0.967	1.003	1.2 X radial
4	E1-30d	16-Sep-2022	0.792	0.793	0.251	1.209	1.353	none
5	E1-10d	06-Oct-2022	---	0.061	0.030	0.117	0.149	none
Launch-->EGA1 (All TCM)			***14.857***	***19.347***	***2.101***	***23.257***	***24.779***	--
7	Post-EGA Cleanup	26-Oct-2022	---	3.953	2.663	9.344	12.094	none
8	DSM-2 (ME)	02-Feb-2024	897.993	898.058	2.971	903.116	904.973	3 X radial
9	DSM-2 Cleanup	16-Feb-2024	---	6.582	2.907	11.558	14.314	3 X radial
10	E2-30d	13-Nov-2024	5.376	5.706	1.339	8.156	10.222	1.06 X radial
11	E2-10d	03-Dec-2024	0.581	0.631	0.139	0.867	1.003	none
EGA1-->EGA2 (TCM Only)			***5.957***	***16.872***	***4.511***	***25.195***	***29.556***	--
13	Post-EGA Cleanup	12-Jan-2025	0.182	12.565	5.229	21.589	26.923	none
14	Dj-30d	21-Mar-2025	---	0.437	0.229	0.885	1.118	none
15	Dj-7d	13-Apr-2025	---	0.065	0.034	0.127	0.166	none
EGA2-->Donaldjohanson (All TCM)			***0.182***	***13.068***	***5.344***	***22.442***	***27.712***	--
17	DSM-3 (ME)	03-Apr-2027	311.099	297.458	12.709	319.149	328.534	none
18	DSM-3 Cleanup	17-Apr-2027	---	2.304	1.002	4.117	4.963	none
19	Eu-30d	13-Jul-2027	---	0.171	0.098	0.361	0.492	none
20	Eu-7d	05-Aug-2027	---	0.134	0.074	0.266	0.354	none
Donaldjohanson-->Eurybates (TCM Only)			***0.000***	***2.609***	***1.062***	***4.569***	***5.367***	--
22	Polymele DSM (Po-27d)	19-Aug-2027	0.427	26.314	14.791	53.282	72.569	none
23	Po-7d	08-Sep-2027	---	1.031	0.881	2.683	4.500	none
Eurybates-->Polymele (All TCM)			***0.427***	***27.345***	***15.467***	***55.881***	***74.694***	--
25	DSM-4 (ME)	29-Sep-2027	122.117	125.549	3.877	131.843	134.875	none
26	DSM-4 Cleanup	13-Oct-2027	---	0.936	0.408	1.674	1.985	none
27	Le-30d	19-Mar-2028	---	0.361	0.220	0.776	1.024	none
28	Le-7d	11-Apr-2028	---	0.135	0.083	0.302	0.385	none
Polymele-->Leucus (TCM Only)			***0.000***	***1.432***	***0.488***	***2.253***	***2.803***	--
30	Post-Leucus Cleanup	18-May-2028	---	0.754	0.359	1.443	1.734	none
31	DSM-5 (ME)	23-Jul-2028	346.686	346.650	1.129	348.508	349.089	none
32	DSM-5 Cleanup	06-Aug-2028	---	2.715	1.207	4.862	5.907	none
33	Or-30d	12-Oct-2028	---	0.314	0.179	0.662	0.856	none
34	Or-7d	04-Nov-2028	---	0.171	0.107	0.379	0.497	none
Leucus-->Orus (TCM Only)			***0.000***	***3.953***	***1.309***	***6.206***	***7.342***	--
36	Post-Orus Cleanup	07-Jan-2029	0.708	0.855	0.392	1.542	1.976	1.7 X radial
37	E3-30d	26-Nov-2030	---	2.720	1.036	4.645	6.118	none
38	E3-10d	16-Dec-2030	---	0.137	0.080	0.278	0.404	none
Orus-->EGA3 (All TCM)			***0.089***	***3.712***	***1.336***	***6.121***	***7.864***	--
40	Post-EGA Cleanup	05-Jan-2031	0.814	8.549	4.593	17.312	21.461	none
41	Pa-30d	31-Jan-2033	---	4.434	3.557	11.992	16.732	none
42	Pa-7d	23-Feb-2033	---	0.334	0.212	0.735	1.058	none
EGA3-->Patroclus (All TCM)			***0.814***	***13.318***	***6.763***	***26.479***	***31.756***	--
Total for Main Engine (ME) Thruster			**1677.895**	**1667.715**	**9.775**	**1684.256**	**1692.041**	--
Total for TCM Thrusters			**22.944**	**101.680**	**22.710**	**145.348**	**170.183**	--
TOTAL MISSION			**1700.839**	**1769.395**	**32.485**	**1829.604**	**1862.224**	--

Depending on the trajectory's complexity, one can achieve significant reduction in statistical maneuver ΔV when the re-optimization no longer limits each ΔV to target the spacecraft state at the next trajectory-altering point (flyby close approach or DSM initial thrust at a fixed epoch) on an invariant full-mission spacecraft reference trajectory. With re-optimization, selected TCMs are allowed to shift with corresponding constraints that enforce minimum time between consecutive TCMs. With re-optimization, the closest approach epoch of the next Trojan encounter is permitted to shift slightly. The first step of this updated Lucy statistical maneuver analysis included performing trajectory optimization for the deterministic maneuvers from DSM 3 through the second TCM before the third Earth gravity-assist flyby. This "partial" trajectory re-optimization spanned nearly half of the mission's planned maneuvers. As a baseline for comparing improvement achieved between no re-optimization and partial trajectory re-optimization, Tables 4 and 5 shown various statistical and the deterministic ΔVs and EGA perigee target bias scale factors to meet the mission's 1% minimum probability of Earth atmospheric entry if no planned TCMs were possible. The EGA target bias scale factors indicate how far the perigee target had to shift in the Earth-spacecraft radial direction. The number of TCMs as listed in the Introduction changed after this analysis was done.

Table 5. Launch Close Mission ΔV Usage *without* Re-optimization (m/s)

TCM	*Purpose/Timing*	*Nominal Epoch*	*Deterministic*	*Mean*	*Std. Dev.*	*95%*	*99%*	*Target Bias*
1	Injection Correction	05-Dec-2021	0.007	6.164	3.226	12.185	15.692	none
2	DSM-1 (TCM)	29-Jul-2022	142.498	143.122	0.730	144.273	144.758	3 X radial
3	DSM-1 Cleanup	12-Aug-2022	1.015	2.364	0.830	3.726	4.389	none
4	E1-30d	01-Oct-2022	---	0.114	0.067	0.241	0.327	none
5	E1-10d	21-Oct-2022	---	0.036	0.017	0.066	0.084	none
Launch-->EGA1 (All TCM)			***1.023***	***8.678***	***3.331***	***14.972***	***18.602***	--
7	Post-EGA Cleanup	10-Nov-2022	---	2.172	1.144	4.243	6.025	none
8	DSM-2 (ME)	24-Sep-2023	772.933	772.908	2.599	777.127	778.778	3 X radial
9	DSM-2 Cleanup	08-Oct-2023	---	5.408	2.358	9.818	11.481	3 X radial
10	E2-30d	13-Nov-2024	5.715	6.394	1.662	9.723	12.404	none
11	E2-10d	03-Dec-2024	---	0.291	0.141	0.553	0.684	none
EGA1-->EGA2 (TCM Only)			***5.715***	***14.265***	***3.464***	***20.599***	***25.069***	--
13	Post-EGA Cleanup	12-Jan-2025	---	12.659	5.424	22.237	27.169	none
14	Dj-30d	21-Mar-2025	---	0.440	0.234	0.913	1.118	none
15	Dj-7d	13-Apr-2025	---	0.065	0.034	0.131	0.178	none
EGA2-->Donaldjohanson (All TCM)			***0.000***	***13.165***	***5.549***	***22.926***	***28.022***	--
17	DSM-3 (ME)	04-Apr-2027	312.105	296.318	13.428	319.625	334.122	none
18	DSM-3 Cleanup	17-Apr-2027	---	2.289	0.996	4.093	4.906	none
19	Eu-30d	13-Jul-2027	---	0.170	0.098	0.358	0.500	none
20	Eu-7d	05-Aug-2027	---	0.134	0.074	0.266	0.354	none
Donaldjohanson-->Eurybates (TCM Only)			***0.000***	***2.593***	***1.056***	***4.531***	***5.395***	--
22	Polymele DSM (Po-27d)	19-Aug-2027	0.819	25.286	14.584	52.518	68.536	none
23	Po-7d	08-Sep-2027	---	0.996	0.855	2.343	4.652	none
Eurybates-->Polymele (All TCM)			***0.819***	***26.282***	***15.236***	***55.161***	***71.946***	--
25	DSM-4 (ME)	29-Sep-2027	118.970	122.740	4.100	129.458	132.738	none
26	DSM-4 Cleanup	13-Oct-2027	---	0.915	0.400	1.646	1.899	none
27	Le-30d	19-Mar-2028	---	0.357	0.218	0.769	1.029	none
28	Le-7d	11-Apr-2028	---	0.136	0.084	0.303	0.386	none
Polymele-->Leucus (TCM Only)			***0.000***	***1.408***	***0.479***	***2.202***	***2.756***	--
30	Post-Leucus Cleanup	18-May-2028	---	0.753	0.357	1.426	1.764	none
31	DSM-5 (ME)	23-Jul-2028	349.150	349.125	1.135	351.005	351.574	none
32	DSM-5 Cleanup	06-Aug-2028	---	2.725	1.211	4.871	5.920	none
33	Or-30d	12-Oct-2028	---	0.313	0.178	0.661	0.842	none
34	Or-7d	04-Nov-2028	---	0.171	0.107	0.375	0.497	none
Leucus-->Orus (TCM Only)			***0.000***	***3.962***	***1.303***	***6.293***	***7.321***	--
36	Post-Orus Cleanup	07-Jan-2029	0.066	0.572	0.270	1.068	1.329	+550 km radial
37	E3-30d	26-Nov-2030	0.175	0.641	0.535	1.687	2.419	none
38	E3-10d	16-Dec-2030	---	0.268	0.198	0.642	0.907	none
Orus-->EGA3 (All TCM)			***0.242***	***1.481***	***0.635***	***2.697***	***3.285***	--
40	Post-EGA Cleanup	05-Jan-2031	---	14.509	8.686	31.336	41.858	none
41	Pa-30d	31-Jan-2033	0.563	4.548	3.697	12.030	17.069	none
42	Pa-7d	23-Feb-2033	---	0.338	0.219	0.756	1.063	none
EGA3-->Patroclus (All TCM)			***0.563***	***19.395***	***9.415***	***36.398***	***47.412***	--
Total for Main Engine (ME) Thruster			**1695.656**	**1684.214**	**10.120**	**1701.018**	**1713.222**	--
Total for TCM Thrusters			**8.362**	**91.229**	**23.492**	**131.040**	**162.916**	--
TOTAL MISSION			**1704.018**	**1775.443**	**33.612**	**1832.058**	**1876.138**	--

Delta-V statistics from the corresponding partial trajectory re-optimization (Tables 6 and 8) not only reveal significant reduction in statistical ΔV, but also indicate a shift in the maximum values of the 99% ΔV for the main engine thruster (bi-propellant) and TCM thrusters (mono-propellant) between the launch period open and close trajectories. The maximum 99 % ΔV for the total mission provides a conservative estimate of the 3-sigma maximum statistical ΔV that, along with the deterministic ΔV, is the primary basis for the ΔV budget. Note that the early deterministic maneuvers (especially DSM-1 and DSM-1 cleanup TCM-3) are scheduled differently for the two launch cases, owing to phasing differences associated with Earth's position at launch and EGA 1 for launch dates 20 days apart. Also, note that the 99 % ΔV total for TCM thrusters provides a conservative estimate of the 3-sigma maximum statistical ΔV (about 122 m/s), which occurs for launch period close. The 1710 m/s main engine 99 % ΔV, is also highest for launch close. The non-margin portion of the mission ΔV budget that results from this analysis are shown in Table 7.

Table 6. Launch Open Mission ΔV Usage *with* TCM 17-36 Re-optimization (m/s)

TCM	Purpose/Timing	Nominal Epoch	Deterministic	Mean	Std. Dev.	95%	99%	Target Bias
1	Injection Correction	15-Nov-2021	0.010	4.263	1.888	7.656	9.234	none
2	DSM-1 (TCM)	19-Apr-2022	13.378	13.383	0.618	14.405	14.858	3 X radial
3	DSM-1 Cleanup	03-May-2022	0.382	0.848	0.069	0.967	1.003	1.2 X radial
4	E1-30d	16-Sep-2022	0.601	0.793	0.251	1.209	1.353	none
5	E1-10d	06-Oct-2022	---	0.061	0.030	0.117	0.149	none
Launch-->EGA1 (All TCM)			***14.370***	***3.953***	***2.663***	***9.344***	***12.094***	--
7	Post-EGA Cleanup	26-Oct-2022	---	3.953	2.663	9.344	12.094	none
8	**DSM-2 (ME)**	**02-Feb-2024**	**897.993**	**898.058**	**2.971**	**903.116**	**904.973**	**3 X radial**
9	DSM-2 Cleanup	16-Feb-2024	---	6.582	2.907	11.558	14.314	3 X radial
10	E2-30d	13-Nov-2024	5.376	5.706	1.339	8.156	10.222	1.06 X radial
11	E2-10d	03-Dec-2024	0.581	0.631	0.139	0.867	1.003	none
EGA1-->EGA2 (TCM Only)			***5.957***	***16.872***	***4.511***	***25.195***	***29.556***	--
13	Post-EGA Cleanup	12-Jan-2025	0.182	12.565	5.229	21.589	26.923	none
14	Dj-30d	21-Mar-2025	---	0.437	0.229	0.885	1.118	none
15	Dj-7d	13-Apr-2025	---	0.065	0.034	0.127	0.166	none
EGA2-->Donaldjohanson (All TCM)			***0.182***	***13.068***	***5.344***	***22.442***	***27.712***	--
17	**DSM-3 (ME)**	**6-Mar-3-May-2027**	**311.070**	**311.138**	**7.415**	**322.887**	**329.493**	**none**
18	DSM-3 + 21d	10-Apr-14-Jun-2027	0.410	3.342	2.151	6.748	9.221	none
19	Eu-30d	13-Jul-2027	---	0.171	0.097	0.347	0.484	none
20	Eu-7d	05-Aug-2027	---	0.139	0.077	0.297	0.371	none
Donaldjohanson-->Eurybates (TCM Only)			***0.410***	***3.652***	***2.196***	***7.209***	***9.641***	--
22	Po-28d - Po-26d	18-20-Aug-2027	1.880	2.659	3.144	10.153	11.702	none
23	Po-7d	08-Sep-2027	---	0.248	0.175	0.600	0.893	none
Eurybates-->Polymele (All TCM)			***1.880***	***2.908***	***3.250***	***10.697***	***12.172***	--
25	**DSM-4 (ME)**	**29-Sep-11-Oct-2027**	**121.590**	**121.215**	**5.397**	**130.811**	**137.286**	**none**
26	DSM-4 + 21d	20-Oct-1-Nov-2027	---	3.281	2.692	8.344	10.844	none
27	Le-30d	19-Mar-2028	---	0.461	0.285	0.992	1.390	none
28	Le-7d	11-Apr-2028	---	0.141	0.082	0.303	0.388	none
Polymele-->Leucus (TCM Only)			***0.000***	***3.882***	***2.881***	***9.322***	***11.992***	--
30	Post-Leucus Cleanup	18-May-2028	---	1.605	0.508	2.553	3.214	none
31	**DSM-5 (ME)**	**16-31 Jul 2028**	**346.900**	**346.866**	**7.076**	**357.605**	**361.825**	**none**
32	DSM-5 + 21d	6-21 Aug 2028	---	4.007	3.537	11.899	18.686	none
33	Or-30d	12-Oct-2028	---	0.223	0.134	0.473	0.671	none
34	Or-7d	04-Nov-2028	---	0.175	0.110	0.382	0.510	none
Leucus-->Orus (TCM Only)			0.000	6.009	3.594	13.514	20.644	--
36	Post-Orus Cleanup	07-Jan-2029	0.038	1.244	0.776	2.698	4.240	1.7 X radial
37	E3-30d	26-Nov-2030	0.350	2.778	1.284	5.025	6.549	none
38	E3-10d	16-Dec-2030	---	0.140	0.088	0.299	0.430	none
Orus-->EGA3 (All TCM)			***0.388***	***4.162***	***1.821***	***7.297***	***9.845***	--
40	Post-EGA Cleanup	05-Jan-2031	0.814	8.673	4.610	17.218	21.780	none
41	Pa-30d	31-Jan-2033	---	4.530	3.594	12.006	15.937	none
42	Pa-7d	23-Feb-2033	---	0.344	0.220	0.763	1.092	none
EGA3-->Patroclus (All TCM)			***0.814***	***13.547***	***6.854***	***25.947***	***33.055***	--
Total for Main Engine (ME) Thruster			**1677.553**	**1677.273**	**7.730**	**1689.801**	**1699.357**	--
Total for TCM Thrusters			**23.590**	**83.447**	**13.112**	**106.989**	**119.190**	--
TOTAL MISSION			**1701.144**	**1760.720**	**20.841**	**1796.790**	**1818.547**	--

Table 7. Lucy Mission Delta-V Budget

	Bi-prop ΔV (m/s)	Mono-prop ΔV (m/s)
Mission Budget (3-sigma maximum)	1710	122
Contingency Margin	12.5	15
Total	1722.5	137

The TCMs included in the partial trajectory re-optimization yielded the majority of potential reduction in 99% ΔV. Due to the prior EMTG low-fidelity Earth flyby limitation, overall mission complexity and time required to conduct Monte Carlo statistical maneuver analysis for the full mission, just under 50% of the full-mission trajectory was reoptimized with all 1000 sample trajectories at each deterministic maneuver. Note that this re-optimized portion of the trajectory represents the longest duration of the mission trajectory with no EGAs but with the largest 99% ΔV (TCM 22) magnitude (> 72 m/s) and the prior DSM (#3) for launch period open. The net 99% ΔV savings resulting from this partial trajectory re-optimization was 3.5 m/s for main engine thruster bi-prop maneuvers and 48.5 m/s for TCM thruster mono-prop maneuvers with ΔV < 50 m/s. With this result available well before launch the formal lowering of ΔV budget exchanged propellant for spacecraft hardware mass helped dry mass margin to be on target for Preliminary Design Review.

Table 8. Launch Close Mission ΔV Usage *with* TCM 17-36 Re-optimization (m/s)

TCM	Purpose/Timing	Nominal Epoch	Deterministic	Mean	Std. Dev.	95%	99%	Target Bias
1	Injection Correction	05-Dec-2021	0.007	6.164	3.226	12.185	15.692	none
2	**DSM-1 (TCM)**	**29-Jul-2022**	**142.498**	**143.122**	**0.730**	**144.273**	**144.758**	**3 X radial**
3	DSM-1 Cleanup	12-Aug-2022	1.015	2.364	0.830	3.726	4.389	none
4	E1-30d	01-Oct-2022	---	0.114	0.067	0.241	0.327	none
5	E1-10d	21-Oct-2022	---	0.036	0.017	0.066	0.084	none
Launch-->EGA1 (All TCM)			***1.023***	***8.678***	***3.331***	***14.972***	***18.602***	--
7	Post-EGA Cleanup	10-Nov-2022	---	2.172	1.144	4.243	6.025	none
8	**DSM-2 (ME)**	**24-Sep-2023**	**772.933**	**772.908**	**2.599**	**777.127**	**778.778**	**3 X radial**
9	DSM-2 Cleanup	08-Oct-2023	---	5.408	2.358	9.818	11.481	3 X radial
10	E2-30d	13-Nov-2024	5.715	6.394	1.662	9.723	12.404	none
11	E2-10d	03-Dec-2024	---	0.291	0.141	0.553	0.684	none
EGA1-->EGA2 (TCM Only)			***5.715***	***14.265***	***3.464***	***20.599***	***25.069***	--
13	Post-EGA Cleanup	12-Jan-2025	---	12.659	5.424	22.237	27.169	none
14	Dj-30d	21-Mar-2025	---	0.440	0.234	0.913	1.118	none
15	Dj-7d	13-Apr-2025	---	0.065	0.034	0.131	0.178	none
EGA2-->Donaldjohanson (All TCM)			***0.000***	***13.165***	***5.549***	***22.926***	***28.022***	--
17	**DSM-3 (ME)**	**4-Mar-3-May-2027**	**310.268**	**310.299**	**6.295**	**319.226**	**325.081**	**none**
18	DSM-3 cleanup	22-Apr-14-Jun-2027	0.577	4.118	3.340	7.672	14.110	none
19	Eu-30d	13-Jul-2027	---	0.164	0.118	0.342	0.501	none
20	Eu-7d	05-Aug-2027	---	0.138	0.078	0.295	0.374	none
Donaldjohanson-->Eurybates (TCM Only)			***0.577***	***4.420***	***3.422***	***7.989***	***14.390***	--
22	Po-28d - Po-26d	18-20-Aug-2027	1.877	3.303	2.814	9.860	11.722	none
23	Po-7d	08-Sep-2027	---	0.271	0.172	0.610	0.870	none
Eurybates-->Polymele (All TCM)			***1.877***	***3.573***	***2.911***	***10.428***	***12.257***	--
25	**DSM-4 (ME)**	**28-Sep-7-Oct-2027**	**119.992**	**119.653**	**4.643**	**126.916**	**131.257**	**none**
26	DSM-4 + 21d	19-28-Oct-2027	---	2.983	2.642	8.162	10.324	none
27	Le-30d	19-Mar-2028	---	0.449	0.277	0.978	1.376	none
28	Le-7d	11-Apr-2028	---	0.145	0.084	0.310	0.401	none
Polymele-->Leucus (TCM Only)			***0.000***	***3.576***	***2.825***	***9.100***	***11.432***	--
30	Post-Leucus Cleanup	18-May-2028	---	0.752	0.502	1.749	2.329	none
31	**DSM-5 (ME)**	**16-31 Jul 2028**	**347.816**	**348.051**	**5.326**	**355.828**	**359.274**	**none**
32	DSM-5 + 21d	6-21 Aug 2028	---	3.873	3.286	10.650	17.619	none
33	Or-30d	12-Oct-2028	---	0.220	0.137	0.441	0.700	none
34	Or-7d	04-Nov-2028	---	0.179	0.113	0.396	0.524	none
Leucus-->Orus (TCM Only)			0.000	5.024	3.320	11.536	18.809	--
36	Post-Orus Cleanup	07-Jan-2029	0.066	6.019	0.713	7.060	8.390	+550 km
37	E3-30d	26-Nov-2030	0.193	5.583	3.244	12.104	15.351	none
38	E3-10d	16-Dec-2030	---	0.230	0.149	0.519	0.724	none
Orus-->EGA3 (All TCM)			***0.259***	***11.831***	***3.438***	***18.820***	***21.900***	--
40	Post-EGA Cleanup	05-Jan-2031	---	11.231	5.729	21.542	30.360	none
41	Pa-30d	02-Feb-2033	0.563	5.292	4.283	13.965	19.290	none
42	Pa-7d	25-Feb-2033	---	0.364	0.239	0.837	1.147	none
EGA3-->Patroclus (All TCM)			***0.563***	***16.887***	***8.492***	***33.403***	***41.832***	--
Total for Main Engine (ME) Thruster			**1693.508**	**1694.034**	**6.859**	**1704.012**	**1709.711**	--
Total for TCM Thrusters			**10.014**	**81.420**	**15.084**	**109.031**	**121.720**	--
TOTAL MISSION			**1703.522**	**1775.454**	**21.943**	**1813.043**	**1831.430**	--

RESULTS FOR FULL TRAJECTORY RE-OPTIMIZATION

The incorporation of multiple updates to spacecraft properties, maneuver execution error modeling, orbit determination covariances, launch injection dispersions, and planetary body ephemerides were accounted for with a recent update to the full mission reference trajectory. Spacecraft property updates included an increase in launch mass from 1435 kg to 1550 kg (1520 kg as of the reference trajectory update and the most current analysis in this paper), changes to spacecraft reflectance properties and the spacecraft's Sun-facing surface area. This optimized reference trajectory with ten deterministic maneuvers and a 1696.8 m/s total ΔV applies to the launch period open trajectory that will start on October 16, 2021. This reference trajectory is the basis for statistical maneuver analysis for 1000 trajectories subject to updated sources of trajectory perturbation both without trajectory re-optimization (return to the reference trajectory with each deterministic maneuver design) and with trajectory re-optimization.

As with the prior versions of trajectory design and optimization, Lucy Trajectory Optimization team members at NASA Goddard Space Flight Center use low-fidelity and high-fidelity versions of EMTG to produce an optimal full-mission reference trajectory with minimum propellant usage. This trajectory design is sent to Lockheed Martin Mission Design team and KinetX Maneuver team to create a slightly higher fidelity version of the reference trajectory. Every trajectory (single reference or 1000 sample perturbed) and the resulting maneuver statistics presented in this paper are the direct result of the last, highest fidelity step of this process.

The most recent statistical maneuver analysis for the new launch period open trajectory has reached began at launch and has currently progressed past the initial conditions of the partial trajectory re-optimization discussed earlier. A significant portion of the differences between the PDR and CDR statistical maneuver analyses originate from changes in the spacecraft (surface area and reflectance, heavier initial mass) and more efficient trajectory optimization (shifting ΔV to more efficient bipropellant maneuvers when helpful). Tables 9 and 10 provide the full trajectory re-optimization statistical maneuver ΔV statistics for the newest reference trajectory except for the no re-optimization version of this newest reference trajectory in the column "99% NoReopt" and the partial trajectory re-optimization "99% PDR" 99 percentile ΔV statistics from the Project's Preliminary Design Review (PDR). The "99% NoReopt" case refers to performing a full statistical analysis without altering the reference trajectory epochs of any maneuver or encounter.

A summary of the change in 99% ΔV at the bottom of Table 9 reveals a 26.239 m/s TCM thruster reduction and a Main Engine thruster 16.504 m/s increase between the Flight Dynamics' PDR and CDR (Critical Design Review) statistical maneuver results from launch through the main-belt asteroid Donaldjohanson encounter. A summary of the change in 99% ΔV at the bottom of Table 10 reveals a 2.508 m/s TCM thruster reduction and a Main Engine thruster 11.721 m/s reduction between the Flight Dynamics' PDR and CDR (Critical Design Review) statistical maneuver results from launch through the Donaldjohanson asteroid encounter and up to the first Jupiter Trojan (Eurybates) encounter. The mission leg statistical ΔV summaries of TCMs with individual ΔV magnitudes less than 50 m/s are the square root of the sum of the squared values of the TCMs represented in each leg – not simply the sum of the statistical ΔVs.

Table 9. Launch Open Mission Estimated ΔV Usage *with and without* Re-optimization from Launch to the Asteroid Donaldjohanson Encounter (m/s)

Delta-V Statistics [m/s] for Lucy Launch Day 1								
TCM	***Purpose/Timing***	***Nominal Epoch (UTC)***	***Deterministic***	***Mean***	***95%***	***99%***	***99% NoReopt***	***99% PDR***
1	Injection Correction	15-Nov-2021 16:50:00	3.450	3.596	5.463	6.169	7.583	9.234
2	2nd Injection Correction	30-Dec-2021 17:00:00	---	0.000	0.000	0.000	0.000	--
3	DSM-1 (TCM)	20-Apr-2022 05:20:31	1.595	0.184	0.429	0.599	0.901	14.858
4	DSM-1 Cleanup	03-May-2022 17:00:00	---	0.003	0.019	0.068	0.066	9.675
5	EGA1-30d	16-Sep-2022 17:00:00	---	3.684	3.856	3.931	6.774	6.857
6	EGA1-10d	06-Oct-2022 17:00:00	---	0.154	0.279	0.359	1.607	0.149
Launch-->EGA1 (All TCM)			***5.045***	***7.621***	***9.584***	***10.409***	***15.965***	***24.779***
7	1st EGA1 Cleanup	26-Oct-2022 17:00:00	---	0.535	2.050	3.797	33.999	9.344
8	2nd EGA1 Cleanup	15-Nov-2022 17:00:00	---	0.000	0.000	0.000	0.000	--
9	**DSM-2 (ME)**	**06-Feb-2024 23:32:05**	***909.649***	***914.440***	***919.568***	***921.477***	***916.316***	***904.973***
10	DSM-2 Cleanup	20-Feb-2024 17:00:00	---	8.196	15.515	17.438	17.479	14.314
11	E2-30d	13-Nov-2024 17:00:00	---	5.813	8.244	9.491	9.298	10.222
12	E2-10d	03-Dec-2024 17:00:00	---	0.276	0.509	0.664	0.598	1.003
EGA1-->EGA2 (TCM)			---	***14.820***	***22.166***	***26.678***	***50.233***	***29.556***
EGA1-->EGA2 (ME)			***909.649***	***914.440***	***919.568***	***921.477***	***916.316***	***904.973***
13	1st EGA2 Cleanup	23-Dec-2024 17:00:00	---	11.114	21.366	27.563	20.957	26.923
14	2nd EGA2 Cleanup	12-Jan-2025 17:00:00	0.221	0.371	0.728	0.925	0.353	--
15	Dj-30d	21-Mar-2025 17:00:00	---	0.137	0.322	0.456	0.455	1.118
16	Dj-7d	13-Apr-2025 17:33:00	---	0.046	0.084	0.103	0.101	0.166
EGA2-->Donaldjohanson (All TCM)			***0.221***	***11.669***	***22.037***	***28.373***	***21.367***	***27.712***
Launch-->Donaldjohanson (ME)			***909.649***	***914.440***	***919.568***	***921.477***	***916.316***	***904.973***
Launch-->Donaldjohanson (TCM)			***5.266***	***34.110***	***47.713***	***55.808***	***74.594***	***82.047***
ΔV99 savings Launch to Donaldjohanson (full reoptimization CDR vs. PDR)					**TCM:**	**26.239**	**ME (DSM):**	**-16.504**

Additional progress on trajectory re-optimization with statistical maneuver analysis in completing the launch period open and also applying to the launch open close trajectory will provide the most realistic, yet still conservative update to the mission's ΔV budget.

Table 10. Launch Open Mission Estimated ΔV Usage *with and without* Re-optimization from the Asteroid Donaldjohanson Encounter to the Eurybates Encounter (m/s)

Delta-V Statistics [m/s] for Lucy Launch Day 1								
TCM	***Purpose/Timing***	***Nominal Epoch (UTC)***	***Deterministic***	***Mean***	***95%***	***99%***	***99% NoReopt***	***99% PDR***
17	Dj Cleanup	20-May-2025 17:00:00	---	0.060	0.065	0.091	0.455	0.000
18	**DSM-3 (ME)**	**03-Apr-2027 03:52:08**	***310.648***	***312.096***	***315.409***	***316.813***	***312.950***	***328.534***
19	DSM-3 Cleanup	17-Apr-2027 17:00:00	---	3.039	5.493	6.829	5.645	4.963
20	Eurybates-30d	13-Jul-2027 17:00:00	---	0.129	0.275	0.380	0.369	0.492
21	Eurybates-7d	05-Aug-2027 01:49:37	---	0.085	0.169	0.206	0.228	0.354
Donaldjohanson-->Eurybates (TCM)			---	***3.314***	***5.921***	***7.133***	***6.995***	***9.641***
ΔV99 savings Donaldjohanson to Eurybates (full reoptimization CDR vs. PDR)					**TCM:**	**2.508**	**ME (DSM):**	**11.721**

RELAIBLE ENCOUNTER TARGETING SHOWN WITH 3-SIGMA ERROR ELLIPSES

The ultimate objective of conducting Lucy mission maneuvers is to precisely deliver the spacecraft to Trojan asteroid flyby target conditions that are optimized within the geometric limitations inherent with the heliocentric trajectory. The ability to successfully arrive at the five Trojan encounter events depends on the successful targeting of three Earth gravity-assist flybys and a practice encounter with mainbelt asteroid Donaldjohanson. The figures in this section provide a chronological account of the expected 3-sigma (conservatively estimated using 99% probability ΔV maneuver execution uncertainties) B-plane error ellipses for all precursor and Trojan encounters. Not included with the graphical error ellipse results are the numerical values of the major and minor error ellipse dimensions and the variation in projected arrival time for each maneuver.

Error ellipses for maneuvers that target the three EGAs are shown in Figures 1, 2, 3, 4, 10, and 11. Figure 5 corresponds to the Donaldjohanson asteroid encounter. Figures 6-9 and 12 reveal the target ellipses for the four L_4 Trojan asteroid encounters and the L5 trojan binary system. Each error ellipse is a conservative 3-sigma two-dimensional B-plane representation of where the spacecraft would pass (if no following TCM is completed) relative to the encounter body in Earth Mean Equator and Equinox of January 1, 2000 reference frame (EME2000) at the minimum approach distance. Each of these error ellipses apply to the launch period open launch date trajectory. The nomenclature for TCMs 1-21 corresponds to the newest CDR analysis and the remaining TCM numbers are for PDR.

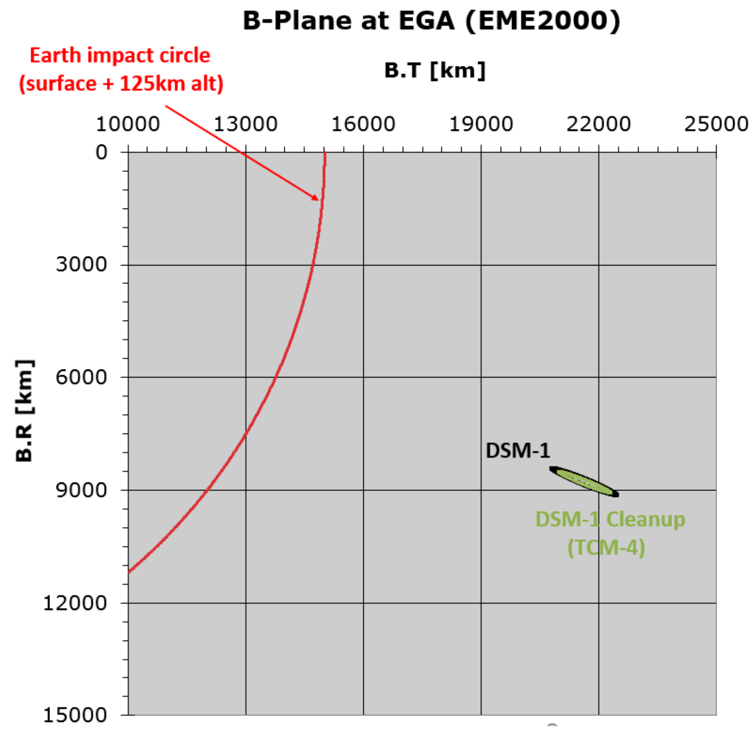

Figure 1. EGA 1 Error Ellipses for DSM 1 (TCM 3) and TCM 4 with a 100% Radial Target Bias

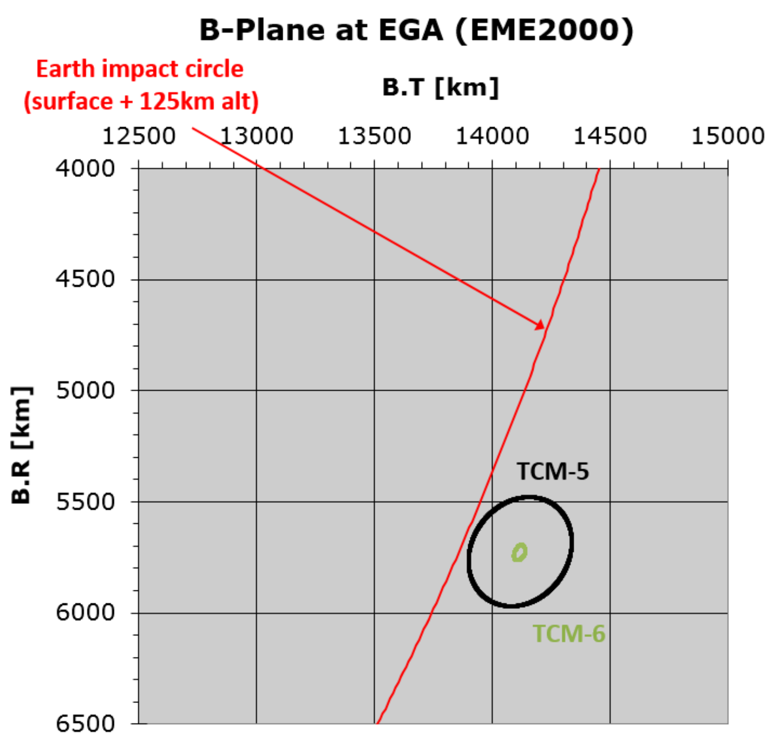

Figure 2. EGA 1 Error Ellipses for TCMs 5 and 6 with no Target Bias

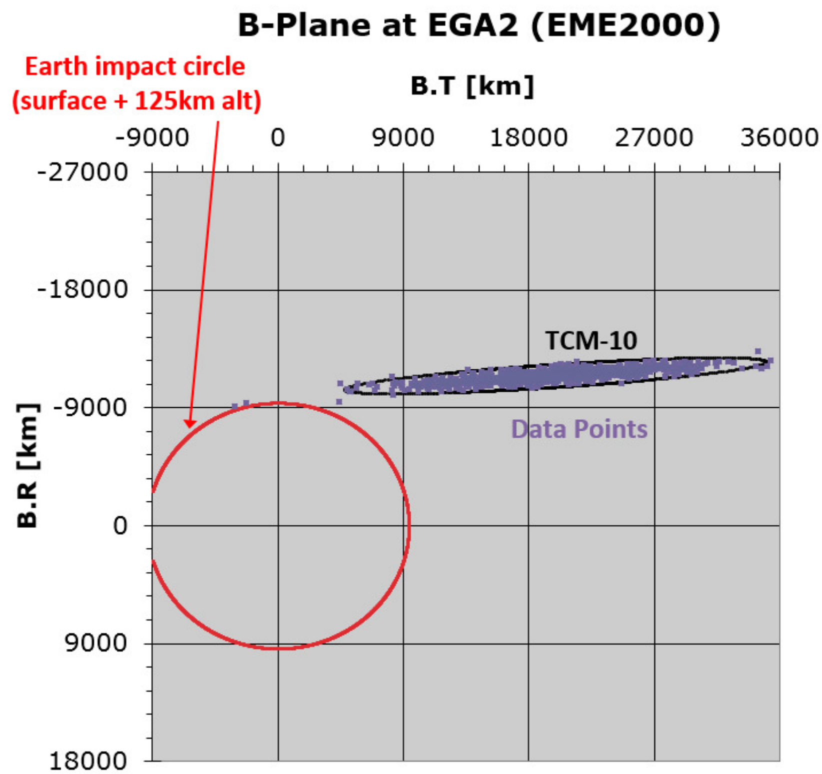

Figure 3. EGA 2 Error Ellipse for TCM 10 with a 200% Radial Target Bias

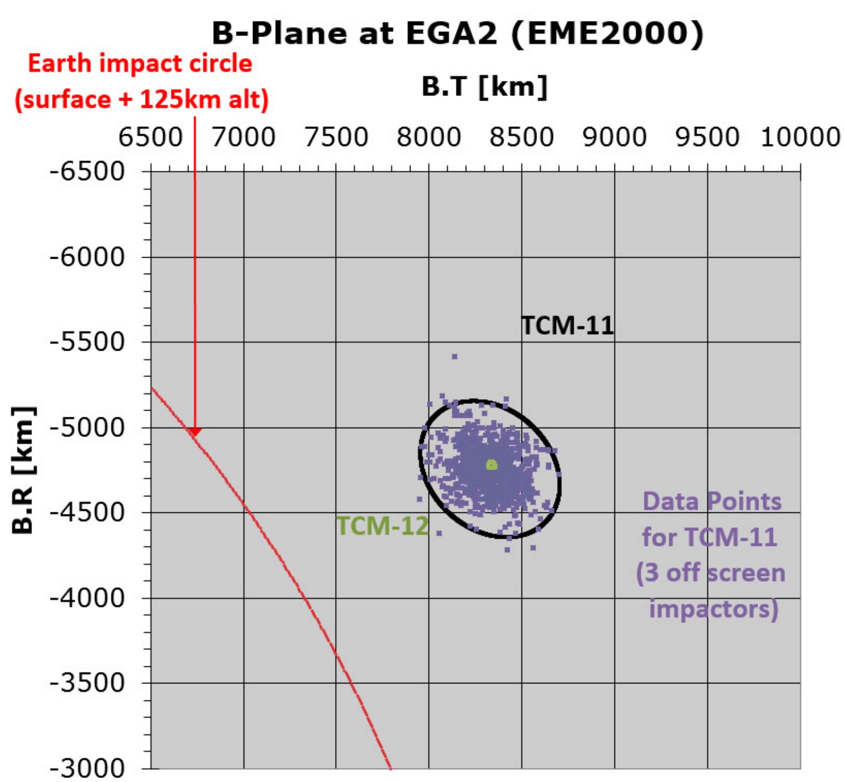

Figure 4. EGA 2 Error Ellipses for TCMs 11 and 12 with no Target Bias

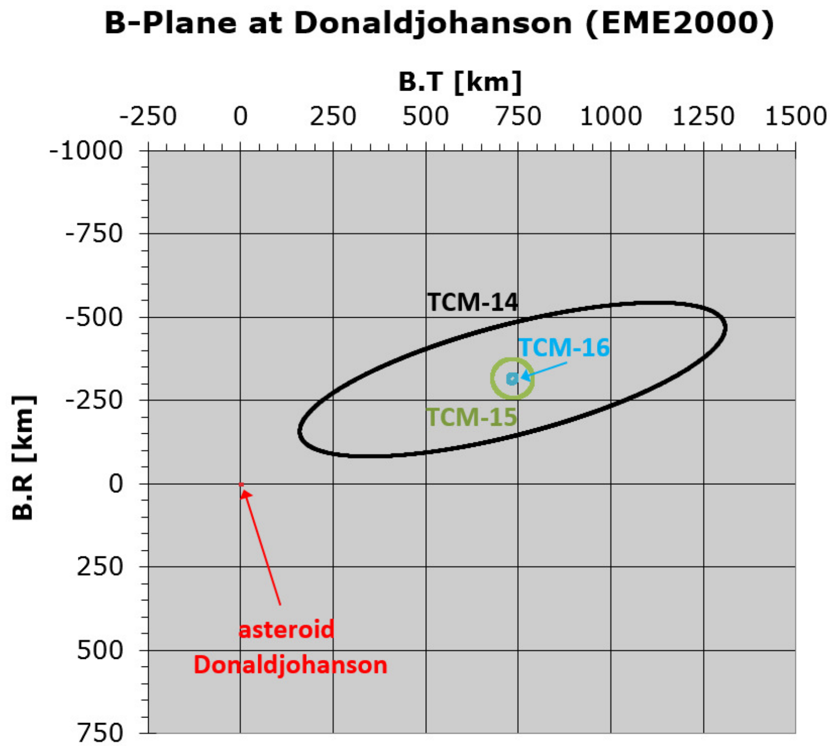

Figure 5. Donaldjohanson Error Ellipses for TCMs 14 to 16

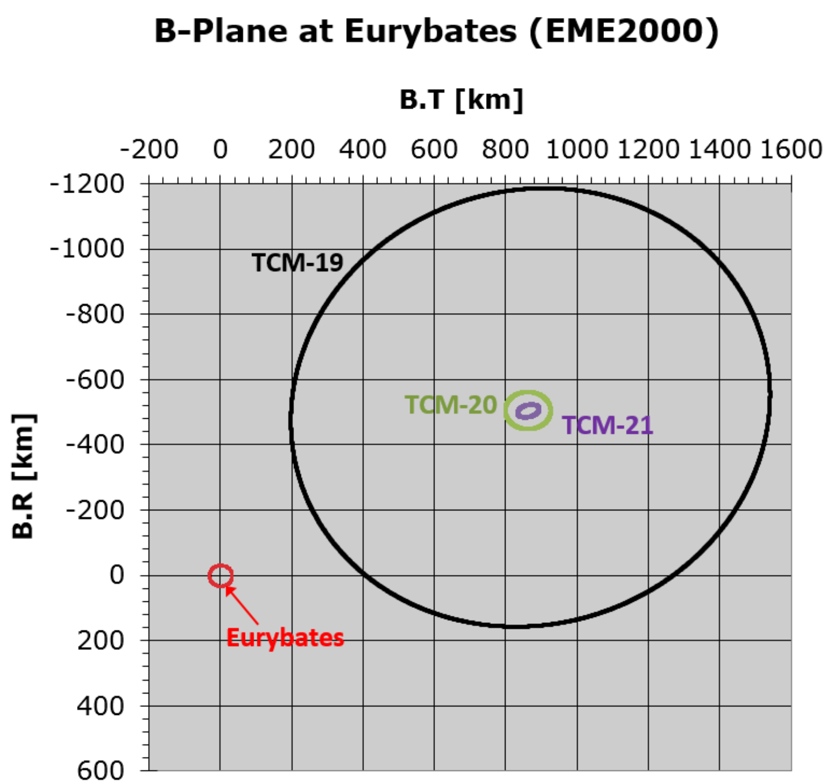

Figure 6. Trojan Eurybates Error Ellipses for TCMs 19 to 21

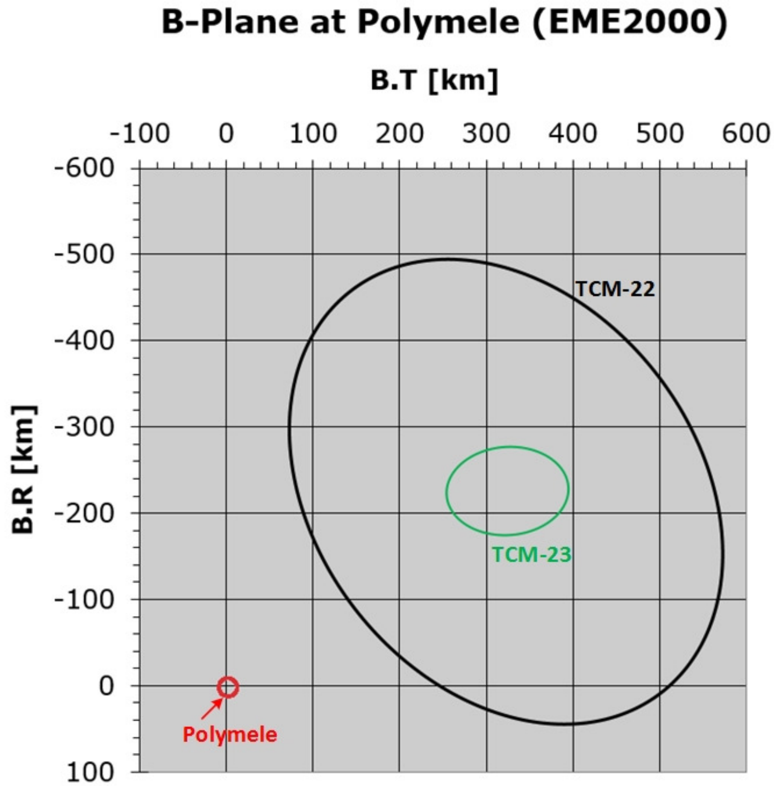

Figure 7. Trojan Polymele Error Ellipses for TCMs 22 and 23

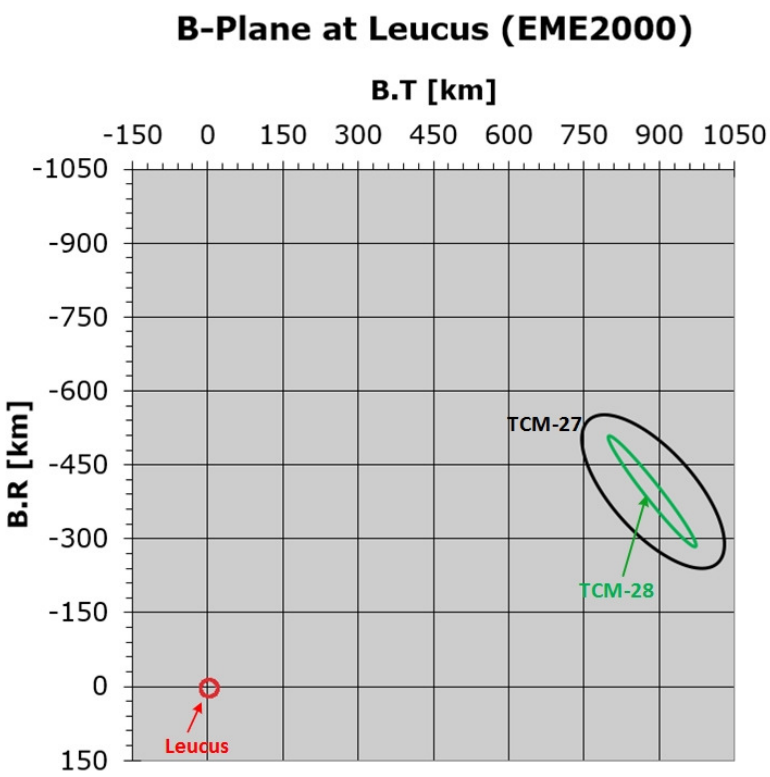

Figure 8. Trojan Leucus Error Ellipses for TCMs 27 and 28

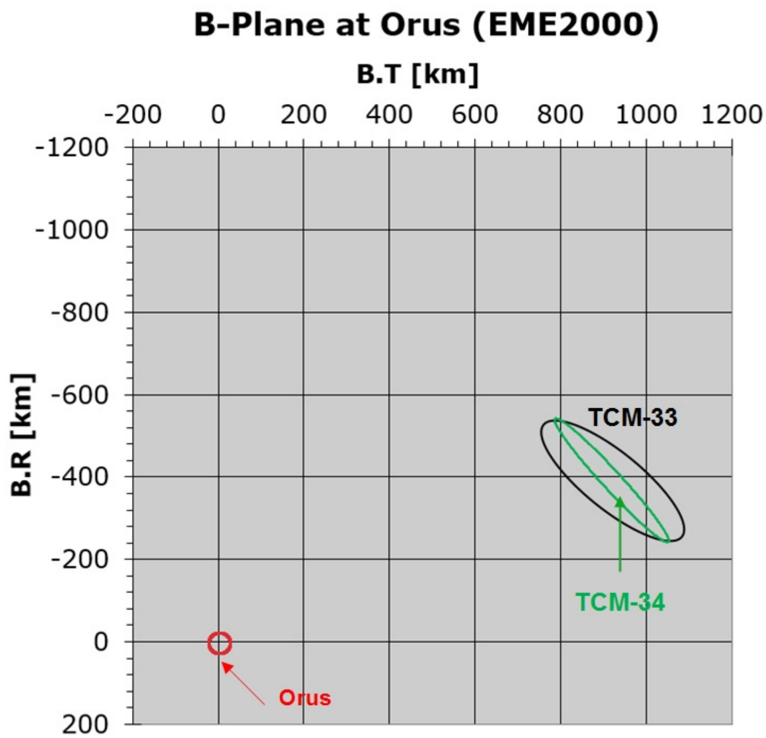

Figure 9. Trojan Orus Error Ellipses for TCMs 33 and 34

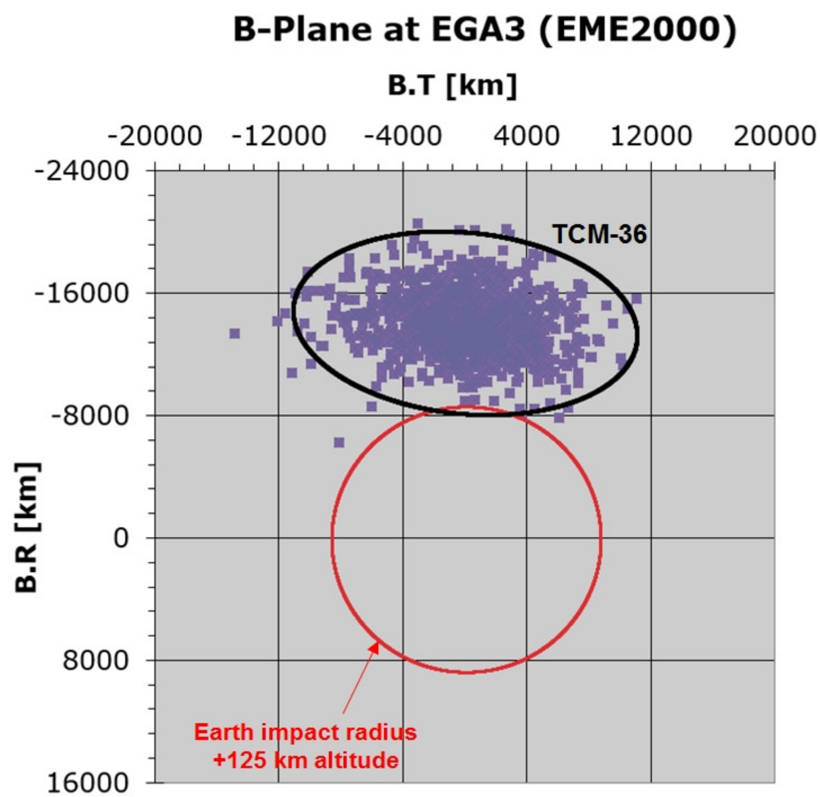

Figure 10. EGA 3 Error Ellipse for TCM 36 with a 70% Radial Target Bias

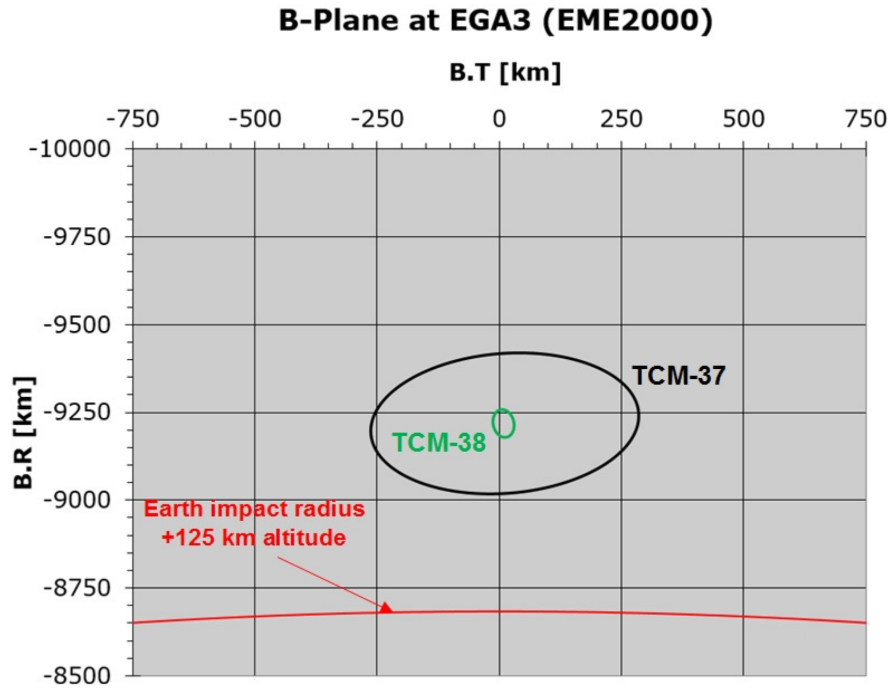

Figure 11. EGA 3 Error Ellipses for TCMs 37 and 38 with no Target Bias

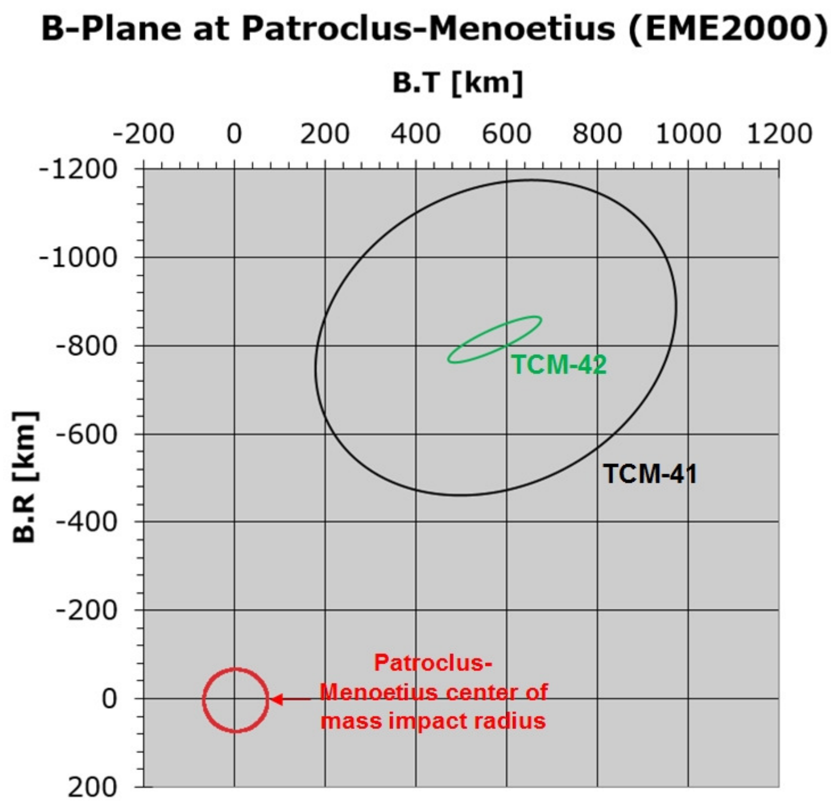

Figure 12. Trojan Binary Patroclus-Menoetius Error Ellipses for TCMs 41 and 42

CONCLUSIONS

Throughout all pre-launch design and development phases updates to the Lucy mission's statistical maneuver analysis have brought more realism to the ΔV budget via moving toward the in-flight trajectory optimization practice with every maneuver design. Improvements made by combining trajectory re-optimization with deterministic maneuver design for each of 1000 sample trajectories applied to the maximum ΔV trajectories in the 21-day launch period have enabled refinement of the mission's ΔV budget. Refinement of this ΔV budget helped with spacecraft mass margin as propellant mass was exchanged for spacecraft dry mass just before the mission's Preliminary Design Review. With three Earth gravity-assist flybys and multiple maneuvers targeting each of the flybys, the Lucy statistical maneuver analysis incorporated radially scaled perigee offsets from the ideal reference trajectory targets. Implementation of this perigee target offset with a target walk-in strategy to the ideal perigee targets two maneuvers before each EGA ensured compliance with a Project requirement that, if no future TCM were possible, the spacecraft would have less than a 1% probability of entering Earth's atmosphere. Upcoming progress on statistical maneuver analysis before launch will complete the refinement of the mission ΔV budget, including incorporation of delayed DSM contingencies.

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REFERENCES

[1] Stanbridge, D., Williams, K., Williams, B., Jackman, C., Weaver, H., Berry, K., Sutter, B., and Englander, J. A., "Lucy: Navigating a Jupiter Trojan Tour", AAS 17-632, AAS/AIAA Astrodynamics Specialist Conference, Minneapolis, MN, August 2017.

[2] Englander, J. A. et. al, "Optimization of the Lucy Interplanetary Trajectory via Two-Point Direct Shooting", AAS 19-663, AAS/AIAA Astrodynamics Specialist Conference, Portland, ME, August 2019.

[3] Ellison, D. H. and Englander, J. A., "High-Fidelity Multiple-Flyby Trajectory Optimization Using Multiple Shooting", AAS 19-661, AAS/AIAA Astrodynamics Specialist Conference, Portland, ME, August 2019.

[4] Knittel, J., Hughes, K., Englander, J., and Sarli, B., "Automated Sensitivity Analysis of Interplanetary Trajectories for Optimal Mission Design," International Symposium on Space Flight Dynamics, Matsuyama, Japan, June 2017.

[5] Gill, P.E., Murray, M., and Saunders, M. A., "SNOPT: An SQP Algorithm for Large-Scale Constrained Optimization," SIAM J. Optimization, Vol. 12, January 2002, pp. 979–1006, 10.1137/s1052623499350013.