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LUCY MISSION DESIGN STRATEGY IN A DYNAMIC OPERATIONS ENVIRONMENT FROM LAUNCH THROUGH FIRST ASTEROID ENCOUNTER

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Lucy, a 12-year long NASA Discovery-class mission which launched on October 16, 2021, will fly by several Jupiter-Trojan asteroids at the L4 and L5 Lagrange points. Prior to the L4 Trojan encounters in 2027 and 2028, Lucy will utilize two Earth gravity-assist flybys and fly by two main-belt asteroids. After the L4 encounters a third Earth flyby will set up the L5 Trojan encounter in 2033. This paper summarizes the baseline mission plan with focus on the spacecraft trajectory and the corresponding essential trajectory correction maneuvers, as well as how the Lucy team adapted to many unforeseen changes to the spacecraft configuration and added an asteroid target of opportunity that required changes to the baseline mission plan. Refinement of asteroid flyby science requirements after launch also required updates to the baseline Lucy trajectory.

INTRODUCTION

The NASA Discovery Program's Lucy mission, which launched on the first day of its October 2021 twenty-day launch period has completed the first 20% of its 11.4-year trajectory[1] including the first of three Earth gravity-assist flybys and the first of seven planned asteroid flybys. The mission-enabling Earth flybys not only lower launch energy and delta-V (ΔV, also known as velocity change) requirements, but also enable the first-ever flybys of Trojan asteroids[2] 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.

After providing the overall mission design plan as of launch, this paper will chronicle an unusually high number of spacecraft operational and encounter science changes that the flight operations teams had to understand and then adapt ground or onboard processes and software. Each change either in spacecraft performance or a science requirement resulted in changes to operational constraints such as trajectory correction maneuver (TCM) implementation or adding TCMs to target a nearby asteroid early in cruise phase or changing Earth or asteroid flyby periapsis distances. Note that the Navigation and Mission Design scope here of various post-launch changes is only a fraction of total mission impact due to issues that were unknown before launch.

Multiple post-launch updates significantly affected one or more aspects of the Lucy mission's scope including mission design and navigation. Shortly after launch flight operators discovered that

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one of the two large solar arrays did not fully deploy, which led to in-depth investigation, maximizing the array's deployment, culminating in the development and implementation of modified flight operations. Less than a year after launch mission leadership authorized analysis to determine costs and potential benefits of flying close enough to observe a small inner main belt asteroid that came within 64,000 km of the nominal mission trajectory before re-targeting the baseline trajectory. Some months later risk reduction trades considered the benefits of splitting the first bipropellant main engine deep-space maneuver (DSM) into two parts separated by three days. Finally, scientific analysis yielded adjustments to periapsis range or encounter timing for most of the asteroid flybys. The solar array anomaly[3] (SAA) resulted in more conservative implementation of the earliest TCMs, a slightly higher perigee altitude constraint for two of the three Earth flybys to reduce drag-induced torques on Lucy and updated onboard thruster control software. The trajectory optimization, orbit determination, optical navigation, and multiple science and other engineering analyses favored the low-cost addition of a targeted flyby of asteroid 1999 VD57 which was later named (152830) Dinkinesh. This 1 November 2023 asteroid flyby served as a highly useful practice for later asteroid flybys during the mission. Science planning also revealed more optimal flyby periapsis altitudes and encounter times for some of the Trojan asteroid encounters. The mission's largest delta-V expenditure by a significant factor coincided with the first use of the bipropellant main engine in early February 2024. Lessons learned from the Juno Jupiter orbiter mission and other analysis led to a decision to split this maneuver in two parts of 100 m/s delta-V followed by 816 m/s delta-V about three days later.

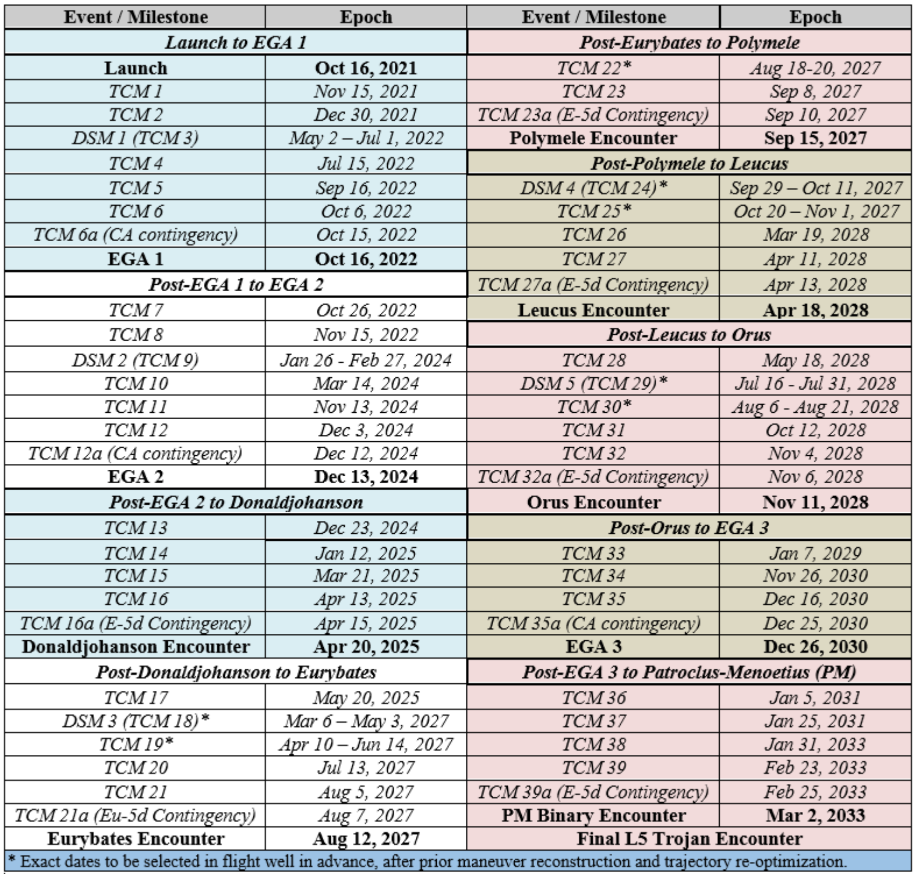
While it is normal for many of the post-launch changes noted above to occur during a mission, all these changes occurring within the first 20% of the nominal mission duration provides evidence for cohesive and highly experienced engineering, science, and management teams. The paper ends with an actual versus planned performance of maneuvers and solar system body flybys completed from launch through the end of 2023.

PRE-LAUNCH MISSION PLAN

The Lucy mission's four operational phases provide a chronological means of segmenting the mission's many solar system body encounters as well as the DSMs and deterministic and statistical TCMs. Launch phase started at Cape Canaveral in Florida with a characteristic energy (C_3) of 28.635 km^2/s^2 (maximum allowable of 29.2 km^2/s^2) and extended until 30 days after launch at the nominal TCM 1 epoch. Initial Cruise phase continues through TCM 3 (also called DSM 1) and the first Earth gravity-assist (EGA 1) flyby one year after launch, then a February 2024 DSM 2 will target the second EGA flyby 2.1 years after EGA 1 which will target the flyby of main-belt asteroid Donaldjohanson in April 2025. After completing this rehearsal for the later Trojan asteroid flybys, 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 end with DSMs 4 and 5 targeting Trojans Leucus and Orus, respectively, in April 2028 and November 2028. The final mission phase, Late Cruise and L5 Trojan Flyby, will utilize DSM 5 and a later third EGA flyby in December 2030 to target a flyby of Jupiter Trojan binary Patroclus and Menoetius in March 2033.

The TCM schedule at launch minimized risk of not meeting flyby target accuracy requirements by using 33 primary maneuver opportunities, one pre-flyby near-Earth object collision avoidance contingency maneuver per EGA flyby, a primary and secondary cleanup TCM after each EGA, and one contingency TCM five days before each asteroid flyby. Table 1 lists TCM epochs and their corresponding target events for the 16 October 2021 launch period open. Statistical TCMs will strategically occur 30 and 10 days before each EGA and 30 and 7 days before each asteroid encounter. With the L4 Trojan Eurybates and Polymele encounters just 34 days apart, the second-to-last targeting TCM will precede the Polymele periapsis by 27 days instead of 30 days to ensure sufficient time from the end of Eurybates flyby science for the maneuver design process through command sequence upload before TCM execution. The contingency TCM option one day before each EGA is there to alter EGA timing to avoid a collision of Lucy with any satellite or debris near Earth.

Table 1. Course-Correction Maneuver Schedule 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-5d Contingency)*	*Sep 10, 2027*
DSM 1 (TCM 3)	*May 2 – Jul 1, 2022*	**Polymele Encounter**	**Sep 15, 2027**
TCM 4	*Jul 15, 2022*	***Post-Polymele to Leucus***	
TCM 5	*Sep 16, 2022*	*DSM 4 (TCM 24)**	*Sep 29 – Oct 11, 2027*
TCM 6	*Oct 6, 2022*	*TCM 25**	*Oct 20 – Nov 1, 2027*
TCM 6a (CA contingency)	*Oct 15, 2022*	*TCM 26*	*Mar 19, 2028*
EGA 1	**Oct 16, 2022**	*TCM 27*	*Apr 11, 2028*
Post-EGA 1 to EGA 2		*TCM 27a (E-5d Contingency)*	*Apr 13, 2028*
TCM 7	*Oct 26, 2022*	**Leucus Encounter**	**Apr 18, 2028**
TCM 8	*Nov 15, 2022*	***Post-Leucus to Orus***	
DSM 2 (TCM 9)	*Jan 26 - Feb 27, 2024*	*TCM 28*	*May 18, 2028*
TCM 10	*Mar 14, 2024*	*DSM 5 (TCM 29)**	*Jul 16 - Jul 31, 2028*
TCM 11	*Nov 13, 2024*	*TCM 30**	*Aug 6 - Aug 21, 2028*
TCM 12	*Dec 3, 2024*	*TCM 31*	*Oct 12, 2028*
TCM 12a (CA contingency)	*Dec 12, 2024*	*TCM 32*	*Nov 4, 2028*
EGA 2	**Dec 13, 2024**	*TCM 32a (E-5d Contingency)*	*Nov 6, 2028*
Post-EGA 2 to Donaldjohanson		**Orus Encounter**	**Nov 11, 2028**
TCM 13	*Dec 23, 2024*	***Post-Orus to EGA 3***	
TCM 14	*Jan 12, 2025*	*TCM 33*	*Jan 7, 2029*
TCM 15	*Mar 21, 2025*	*TCM 34*	*Nov 26, 2030*
TCM 16	*Apr 13, 2025*	*TCM 35*	*Dec 16, 2030*
TCM 16a (E-5d Contingency)	*Apr 15, 2025*	*TCM 35a (CA contingency)*	*Dec 25, 2030*
Donaldjohanson Encounter	**Apr 20, 2025**	**EGA 3**	**Dec 26, 2030**
Post-Donaldjohanson to Eurybates		***Post-EGA 3 to Patroclus-Menoetius (PM)***	
TCM 17	*May 20, 2025*	*TCM 36*	*Jan 5, 2031*
*DSM 3 (TCM 18)**	*Mar 6 – May 3, 2027*	*TCM 37*	*Jan 25, 2031*
*TCM 19**	*Apr 10 – Jun 14, 2027*	*TCM 38*	*Jan 31, 2033*
TCM 20	*Jul 13, 2027*	*TCM 39*	*Feb 23, 2033*
TCM 21	*Aug 5, 2027*	*TCM 39a (E-5d Contingency)*	*Feb 25, 2033*
TCM 21a (Eu-5d Contingency)	*Aug 7, 2027*	**PM Binary Encounter**	**Mar 2, 2033**
Eurybates Encounter	**Aug 12, 2027**	**Final L5 Trojan Encounter**	

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

Overview of Key Trajectory Events

The first planned course correction would be TCM 1 30 days after launch. About six months after launch DSM 1 targeted EGA 1 to occur one year after launch. The ΔV for DSM 1 was small for the first half of the 21-day launch period. With the launch at the first launch opportunity in this launch period, DSM 1 therefore used lower thrust hydrazine TCM thrusters. To prevent the spacecraft having a probability impacting the Earth greater than 1% after each trajectory correction, the EGA target is biased from the optimal target on approach, and this target offset decreases as the b-plane radial errors shrink. This “walk-in strategy” lowers the likelihood of Earth impact if the ability to conduct TCMs ceased before an EGA. An initial EGA target offset and one or more perigee target walk-in (from biased off optimal to optimal) maneuvers were planned between DSM 1 and EGA 1. This strategy was planned 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) has less than a 1% probability of Earth impact without any subsequent TCM. The minimum target altitude for EGA 1 ranged from 300 km to 2390 km across the launch period. Some perigee altitude and asteroid periapsis range values changed after launch.

Lucy's first Earth Gravity-Assist flyby increased Lucy's heliocentric orbit period to about two years with a return to Earth on December 13, 2024. The first orbit after EGA 1 utilizes DSM 2 near aphelion to target EGA 2 perigee, including a 344-km perigee altitude (with appropriate offset to a higher altitude until DSM-2 cleanup TCMs walk in the aim point as mentioned above), to set up a 1000-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 raising the spacecraft orbit aphelion to near Jupiter's orbit distance where the L4 Trojans dwell. The heliocentric trajectory ecliptic plane projection in Figure 1 shows how each EGA increases the size, orbit period, and aphelion distance of the spacecraft's orbit to enable the encounters of the main-belt asteroid and all the Jupiter Trojan asteroids.

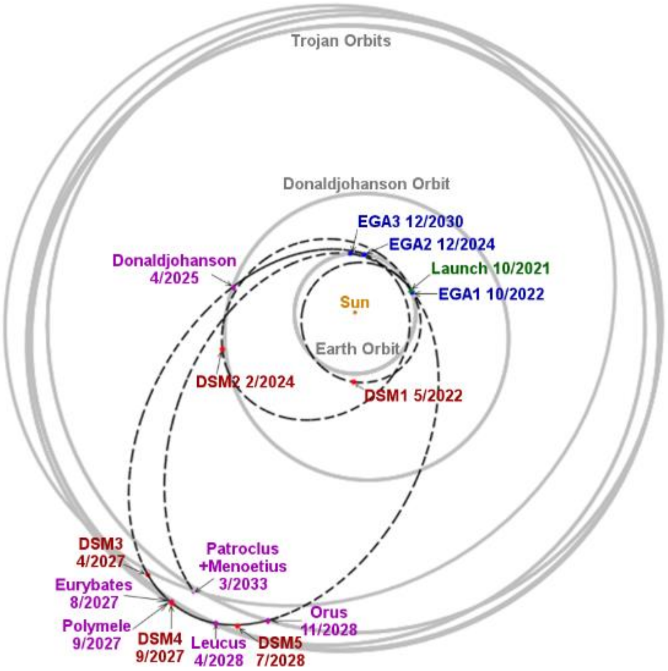


Figure 1. Lucy Heliocentric Trajectory Projection into Earth's Ecliptic (Mean Orbit) Plane.

Two years after flying near asteroid 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 asteroid-relative velocity, 5.67 AU from the Sun, with an 81° approach solar phase angle. Close approach will target 1000 km from Eurybates along the Eurybates to Sun line. Each asteroid flyby periapsis will occur close to the asteroid-to-Sun line.

After the Eurybates encounter, one deterministic TCM and one small statistical TCM will refine the periapsis target near Jupiter Trojan asteroid Polymele on September 15, 2027. Lucy will fly past Polymele at 6.02 km/s asteroid-relative velocity, 5.71 AU from the Sun, with an 82° approach solar phase angle. A small deterministic and one statistical TCM are to be executed 27 days and 7 days before Polymele encounter to improve the encounter delivery accuracy enough to satisfy science goals for the 399-km minimum range Polymele encounter.

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 asteroid-relative velocity, 5.67 AU from the Sun, with a 104° approach solar phase angle. As many as two statistical TCMs 30 days and 7 days before the encounter will refine the encounter delivery accuracy. Leucus periapsis will be targeted to 1000 km.

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 asteroid-relative velocity, 5.33 AU from the Sun, with a 126° approach solar phase angle. Up to two statistical TCMs 30 days and 7 days before the encounter will refine the encounter delivery accuracy to the target. Close approach at Orus will be targeted to 1000 km. After the Orus encounter, statistical maneuvers will refine the EGA3 flyby.

Table 2. Lucy Full-Mission, Final Pre-Launch Monte Carlo Maneuver Summary.

Maneuver	Timing	Epoch	Reference m/s	Mean m/s	σ m/s	95% m/s	99% m/s	Bias
TCM1	Launch+30d	15-NOV-2021	0.648	2.147	1.038	4.003	5.345	
TCM2	Launch+60d	15-DEC-2021		0.040	0.028	0.088	0.121	
TCM3		7-MAY-2022	6.464	6.448	0.397	7.165	7.726	+52% radial bias
TCM4	TCM3+15d	22-MAY-2022		0.792	0.555	1.891	2.416	+15% radial bias
TCM5	EGA1-30d	16-SEP-2022		0.596	0.227	0.976	1.249	
TCM6	EGA1-10d	6-OCT-2022		0.055	0.030	0.108	0.146	
EGA1 Close Approach		16-OCT-2022	$h_{-3\sigma}$ = 283.9 km, h_{mean} = 300.4 km, $h_{3\sigma}$ = 317.0 km					
TCM7	EGA1+30d	15-NOV-2022	0.424	4.586	2.570	9.466	12.190	
DSM2		7-FEB-2024	905.314	905.126	2.996	910.074	912.119	B.R=-5350km bias
TCM10	DSM2+15d	22-FEB-2024		6.748	2.913	12.012	14.385	B.R=-5350km bias
TCM11	EGA2-30d	13-NOV-2024		3.163	1.007	5.259	7.244	
TCM12	EGA2-10	3-DEC-2024		0.164	0.089	0.331	0.481	
EGA2 Close Approach		13-DEC-2024	$h_{-3\sigma}$ = 321.3 km, h_{mean} = 340.7 km, $h_{3\sigma}$ = 360.1 km					
TCM13	EGA2+10d	22-DEC-2024	0.105	7.270	3.745	14.227	18.428	
TCM14	Donaldjohanson-99d	11-JAN-2025		0.113	0.068	0.237	0.312	
TCM15	Donaldjohanson-30d	21-MAR-2025		0.387	0.246	0.849	1.217	
TCM16	Donaldjohanson-7d	13-APR-2025		0.062	0.034	0.124	0.148	
Donaldjohanson Close Approach		20-APR-2025	$R_{-3\sigma}$ = 986.3 km, R_{mean} = 1000.1 km, $R_{3\sigma}$ = 1013.8 km					
TCM17	Donaldjohanson+30d	20-MAY-2025	0.271	0.809	0.435	1.638	2.121	
DSM3		7-APR-2027	312.727	312.748	1.026	314.409	315.034	
TCM19	DSM3+15d	22-APR-2027		2.453	1.044	4.302	5.024	
TCM20	Eurybates-30d	13-JUL-2027		0.162	0.095	0.345	0.446	
TCM21	Eurybates-7d	5-AUG-2027		0.087	0.045	0.170	0.222	
Eurybates Close Approach		12-AUG-2027	$R_{-3\sigma}$ = 968.4 km, R_{mean} = 999.5 km, $R_{3\sigma}$ = 1030.5 km					
TCM22	Polymele-27d	19-AUG-2027	0.256	0.503	0.216	0.888	1.121	
TCM23	Polymele-7d	8-SEP-2027		0.092	0.044	0.172	0.222	
Polymele Close Approach		15-SEP-2027	$R_{-3\sigma}$ = 406.7 km, R_{mean} = 434.0 km, $R_{3\sigma}$ = 461.4 km					
DSM4		29-SEP-2027	115.999	116.006	0.389	116.668	116.890	
TCM25	DSM4+14d	13-OCT-2027		0.849	0.364	1.504	1.852	
TCM26	Leucus-30d	19-MAR-2028		0.129	0.069	0.265	0.334	
TCM27	Leucus-7d	11-APR-2028		0.089	0.048	0.179	0.240	
Leucus Close Approach		18-APR-2028	$R_{-3\sigma}$ = 974.7 km, R_{mean} = 1000.3 km, $R_{3\sigma}$ = 1025.8 km					
TCM28	Leucus+30d	18-MAY-2028		1.320	0.141	1.559	1.655	
DSM5		23-JUL-2028	349.177	347.886	1.157	349.781	350.507	
TCM30	DSM5+21d	13-AUG-2028		2.928	1.243	5.244	6.348	
TCM31	Orus-30d	12-OCT-2028		0.176	0.090	0.346	0.453	
TCM32	Orus-7d	4-NOV-2028		0.093	0.049	0.188	0.260	
Orus Close Approach		11-NOV-2028	$R_{-3\sigma}$ = 961.6 km, R_{mean} = 1000.2 km, $R_{3\sigma}$ = 1038.7 km					
TCM33	Orus+57d	7-JAN-2029	0.838	1.072	0.316	1.590	1.837	
TCM33A	EGA3-688d	6-FEB-2029		0.026	0.019	0.055	0.073	
TCM34	EGA3-30d	26-NOV-2030		0.532	0.392	1.261	1.703	
TCM35	EGA3-10d	16-DEC-2030		0.055	0.033	0.114	0.160	
EGA3 Close Approach		27-DEC-2030	$h_{-3\sigma}$ = 588.5 km, h_{mean} = 613.1 km, $h_{3\sigma}$ = 637.6 km					
TCM36	EGA3+10d	5-JAN-2031	0.257	6.396	3.324	12.600	15.572	
TCM37	EGA3+30d	25-JAN-2031		0.085	0.056	0.193	0.277	
TCM38	P-M Barycenter-30d	1-FEB-2033		0.415	0.306	1.027	1.371	
TCM39	P-M Barycenter-7d	24-FEB-2033		0.097	0.048	0.185	0.230	
P-M Barycenter Close Approach		3-MAR-2033	$R_{-3\sigma}$ = 1188.6 km, R_{mean} = 1223.5 km, $R_{3\sigma}$ = 1258.4 km					
Launch to P-M Barycenter Summary (DSMs only)			1683.217	1681.766	3.331	1687.161	1689.050	
Launch to P-M Barycenter Summary (TCMs only)			9.263	50.940	7.738	64.388	71.108	

Lucy will use a 626-km nominal-altitude Earth flyby on December 26, 2031, to increase heliocentric orbit inclination by 9° to target Jupiter Trojan asteroids Patroclus and Menoetius. Lucy will fly close to the L5 Jupiter Trojan binary Patroclus and Menoetius on March 2, 2033, at 8.8 km/s asteroid-relative velocity, 5.4 AU from the Sun, with an 18° solar phase angle.

Monte Carlo maneuver analysis (see Table 2 for the final pre-launch full-mission assessment for the actual launch date/time) accounted for orbit tracking data, spacecraft and encounter target asteroid orbit uncertainty, maneuver execution uncertainty based on performance requirements, and orbit improvements from multiple data types including approach optical navigation images. This analysis across the full mission established delta-V and propellant (hydrazine and oxidizer N_2O_4) margins. Hydrazine thrusters are used to impart TCMs with delta-V < 50 m/s, and the bi-propellant engine (N_2O_4) is used for delta-Vs > 50 m/s. Later updates of this analysis for each asteroid encounter helps scientists more precisely plan image mosaics and other science observations because the predicted position variance and time of closest approach variance (predicted versus truth/actual) were both smaller than the more conservative mission encounter variance requirements. The TCMs in Table 2 with non-zero reference delta-Vs are deterministic maneuvers that are not subject to cancellation.

HOW THE SOLAR ARRAY ANOMALY ALTERED OPERATIONS

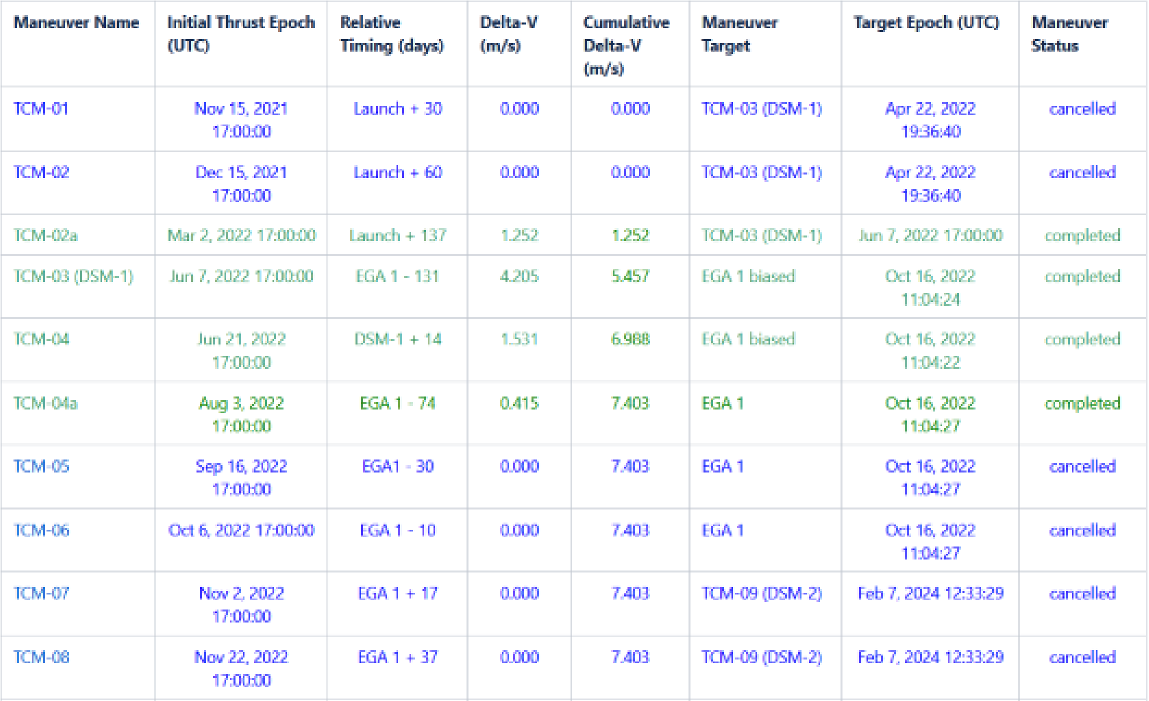
The first of two primary post-launch mission plan changes arose when, shortly after launch, one of two large solar arrays did not fully deploy[3]. Although the +Y-axis solar array failed to latch at the 100% deployed position, careful investigation led to planning, testing, and implementation of multiple solar array re-deployment attempts (RDAs) within the first 14 months after launch. Analysis revealed that deployment of close to 98% was achieved after completing the last planned RDA. With a firm projection of an acceptable power margin throughout the nominal mission and analysis indicating only slightly compromised spacecraft stability throughout structural stressing events such as main engine maneuvers, the maneuver design and trajectory optimization had to adjust to this off-nominal new operational mode.

Course-Correction Maneuver Updates with an Unlatched Solar Array

The SAA investigation led to several changes to the course-correction plan and Earth flyby targeting. Uncertainties in solar array deployment resulted in a more cautious operations approach that included performing smaller test maneuvers rather than implementing the pre-launch course-correction maneuver plan. The combination of highly accurate launch vehicle performance and caution in minimizing torques and thruster accelerations on a spacecraft with a floppy unlatched solar panel, the first two planned TCMs at one and two months after launch were cancelled. The first completed TCM, TCM 2a at 4.5 months after launch, was added after launch to the schedule for Deep Space Network (DSN) tracking and flight operations design and implementation. Instead of having a single TCM 3 with delta-V near 6 m/s several months after launch, the Project took a more conservative approach to study spacecraft response to a 1.25 m/s delta-V 4.5 months after launch co-designed with a 4.2 m/s delta-V 3.2 months later (launch + 7.7 months). Not only did this approach provide helpful information about spacecraft response to smaller thruster firings a few months before the next TCM, but it provided more time for the SAA review board to understand the status of the partially deployed solar panel and to formulate plans to deploy the solar array closer to the latched condition.

Monte Carlo analysis of deterministic and statistical maneuver delta-Vs[4] resulted in cancellation of multiple maneuvers with re-optimizing the remainder of the mission's trajectory[5,6] to minimize the small propellant cost of the cancelled maneuvers and the associated offset from the optimal perigee target achieved at the launch plus one year first Earth flyby. So instead of achieving the lowest possible deviation from the optimal EGA 1 perigee target, statistical TCMs 5, 6, 7, and 8 were cancelled at 30 and 10 days before and 17 and 37 days after perigee, respectively. The TCM 3 cleanup maneuver, TCM 4, also used an off-optimal EGA 1 perigee target to satisfy a Project requirement to keep the probability of Earth impact below 1% if no more thruster activity were possible before EGA 1 for any maneuver that directly targets Earth perigee. This was assessed both by analytical methods that confirmed 10 or fewer trajectory samples out of 1000 intersecting a B-plane representation of Earth plus 125 km altitude to simulate atmospheric entry and spacecraft breakup during re-entry. And to keep the EGA 1 minus 30 days TCM-5 delta-V from becoming large, yet another TCM not requested before launch, a new TCM 4a was added to the mission plan at about 2.5 months before EGA 1 to return the biased EGA 1 perigee target to the optimal EGA 1 perigee target since the ellipse of potential dispersed trajectories at EGA 1 perigee yielded less than a 1% Earth impact probability. A highly accurate TCM 4a execution and careful trajectory re-optimization through the remainder of the mission contributed to the cancellation of the next four statistical TCMs as mentioned above. Table 3, which depicts the cancellation of six TCMs (1, 2, 5, 6, 7, and 8) and the addition of two TCMs (2a and 4a) within about 13 months after launch, also provides the timing and target events for each maneuver.

Table 3. Lucy Course-Correction Maneuver Results during Early Cruise.



Maneuver Name	Initial Thrust Epoch (UTC)	Relative Timing (days)	Delta-V (m/s)	Cumulative Delta-V (m/s)	Maneuver Target	Target Epoch (UTC)	Maneuver Status
TCM-01	Nov 15, 2021 17:00:00	Launch + 30	0.000	0.000	TCM-03 (DSM-1)	Apr 22, 2022 19:36:40	cancelled
TCM-02	Dec 15, 2021 17:00:00	Launch + 60	0.000	0.000	TCM-03 (DSM-1)	Apr 22, 2022 19:36:40	cancelled
TCM-02a	Mar 2, 2022 17:00:00	Launch + 137	1.252	1.252	TCM-03 (DSM-1)	Jun 7, 2022 17:00:00	completed
TCM-03 (DSM-1)	Jun 7, 2022 17:00:00	EGA 1 - 131	4.205	5.457	EGA 1 biased	Oct 16, 2022 11:04:24	completed
TCM-04	Jun 21, 2022 17:00:00	DSM-1 + 14	1.531	6.988	EGA 1 biased	Oct 16, 2022 11:04:22	completed
TCM-04a	Aug 3, 2022 17:00:00	EGA 1 - 74	0.415	7.403	EGA 1	Oct 16, 2022 11:04:27	completed
TCM-05	Sep 16, 2022 17:00:00	EGA1 - 30	0.000	7.403	EGA 1	Oct 16, 2022 11:04:27	cancelled
TCM-06	Oct 6, 2022 17:00:00	EGA 1 - 10	0.000	7.403	EGA 1	Oct 16, 2022 11:04:27	cancelled
TCM-07	Nov 2, 2022 17:00:00	EGA 1 + 17	0.000	7.403	TCM-09 (DSM-2)	Feb 7, 2024 12:33:29	cancelled
TCM-08	Nov 22, 2022 17:00:00	EGA 1 + 37	0.000	7.403	TCM-09 (DSM-2)	Feb 7, 2024 12:33:29	cancelled

The 300 km pre-launch perigee altitude constraint was raised to 350 km to ensure spacecraft stability (with one solar array not securely latched) during the first two of the mission's three Earth flybys (the third Earth flyby perigee altitude optimized well above the 350-km new minimum perigee altitude). The Guidance Navigation and Control, Spacecraft Systems, and Thermal engineering teams at Lockheed Martin conducted extensive analysis to determine the more conservative higher perigee altitude constraint for the first two Earth flybys. Total mission delta-V cost increased about 5 m/s with the minimum perigee altitude increasing from 300 to 350 km.

HOW THE ASTEROID DINKINESH FLYBY ENHANCED EARLY OPERATIONS

The second of two significant post-launch mission plan changes occurred when, about a year after launch, an opportunity arose to fly by a small (~0.8 km diameter) S-type inner main-belt asteroid about two years after launch. In late August 2022 a scientist identified an asteroid with a precisely known orbit that would pass close to Lucy's planned trajectory at least one year before the April 2025 "operations rehearsal" flyby of the ~4-km diameter main-belt asteroid Donaldjohanson. Careful study of this asteroid (identified as 1999 VD57 and later named Dinkinesh) flyby opportunity revealed in January 2023 that it would serve as a valuable test of science and operations plans for later Jupiter Trojan asteroid flybys. NASA approved this 4.4 km/s spacecraft-asteroid relative encounter velocity encounter in February 2023. The geometry of the Dinkinesh encounter, with a high approach phase angle of 114°, and corresponding departure phase angle of 62°, is close to those of the Leucus and Orus encounters with approach phase angles of 100° and 121° respectively. This provided the Science and Optical Navigation teams with a more realistic scenario to prepare for the Trojan encounters with the primary rationale being that this new flyby would better test the Terminal Tracking system that optimizes image quality of the observed asteroid.

Costing only about 4% of the full mission's delta-V margin, the Dinkinesh flyby needed only one new deterministic 3.4 m/s delta-V TCM (-8a) on May 9, 2023, with three follow-up statistical cleanup TCM opportunities. Only TCM 8c, on September 29, 2023, was needed, and its delta-V was small. At only 6.2 cm/s delta-V, TCM 8c tested the lower limit of the spacecraft's maneuver execution capability. There was a concern that maneuver execution errors would be too large a percentage of the total delta-V due to startup transients, attitude disturbances, and the initial implementation of a new attitude controller updated to account for the changed spacecraft dynamics due to the unlatched solar array. Post-TCM-8c maneuver performance evaluation revealed that these concerns were unfounded, as TCM 8c was executed 33 days prior to Dinkinesh closest approach on September 29 with very small maneuver execution errors. Science and engineering analysis revealed that a closest approach distance of 425 km would best accommodate science objectives for the November 1, 2023, flyby. How close the actual maneuver delta-Vs and the reconstructed spacecraft-asteroid periapsis location were to planned targets will appear in the "Trajectory and Maneuver Performance Since Launch" section.

Processes Practiced with the Addition of the Dinkinesh Flyby

Adding the Dinkinesh flyby provided multiple useful opportunities to refine and test the limits of spacecraft performance and selected flight operations team processes. While beyond the scope of this paper, numerous asteroid encounter science operations including imaging and instrument pointing and sequence planning were tested for the first time after launch. Optical navigation techniques demonstrated during the MESSENGER Mercury orbiter, New Horizons (Pluto and Arrokoth flybys), and OSIRIS-REx asteroid sample return missions were refined and implemented by the Lucy Navigation team to improve spacecraft and Dinkinesh orbit knowledge and Dinkinesh physical properties[7,8]. Flight team members at KinetX and Lockheed Martin coordinated with NASA/Goddard Space Flight Center (GSFC) and Southwest Research Institute leadership to plan and implement (or cancel if unnecessary) a series of asteroid approach TCMs at times relative to asteroid periapsis that match the schedule for the primary science Jupiter Trojan asteroid encounters. The nominal schedule for the final two asteroid approach maneuvers includes TCMs at encounter periapsis (E) minus 30 days, E-7 days, and a E-7 days backup at E-5 days. However, a solar conjunction (known well before launch) with Sun-Earth-spacecraft angle less than 3° forced the E-30 days TCM to E-33 days to facilitate the availability for TCM planning of more reliable spacecraft orbit data less tainted by solar plasma effects. Shortly after a post-SAA adapted new thruster controller software update was placed on the spacecraft, TCM-8c was performed to impart a delta-V at just twice the minimum allowable 0.03 m/s. Due to the flyby periapsis distance, relative flyby velocity, and small binary system mass, the Radio Science team was unable to accurately compute the mass of Dinkinesh and its unexpected binary system companion that was later named Selam.

HOW SPLITTING THE LARGEST DSM INTO TWO PARTS ALTERED OPERATIONS

The final of three primary post-launch mission plan changes arose early in 2023 when lead engineers referenced the recent Juno Jupiter orbiter mission experience of splitting a major cruise-phase DSM into two maneuvers[9] separated far enough in time to allow a delay of the second part if any anomaly were detected with the first maneuver. Firing the main engine thruster for the first time with the largest maneuver that will consume over half the onboard propellant was deemed to be higher risk than desired. After analysis by Lead Engineers at Lockheed Martin and KinetX a plan was approved to split DSM-2 into a 100 m/s delta-V DSM-2A on January 31, 2024, followed by the 816 m/s delta-V DSM-2B on February 3, 2024. Note the maneuver nomenclature uses uppercase letters after maneuver number for multiple burn or follow-up contingency maneuvers for DSMs and lowercase letters after the lower delta-V TCM maneuver number when that TCM was added to the TCM schedule after launch.

There are primary reasons why splitting DSM-2 into two parts is a prudent risk reduction. First, there is a term known as the "pyro ladder" which allows up to five main engine firings for maneuvers with delta-V exceeding 50 m/s but preferably over 100 m/s to utilize the higher bi-propellant specific impulse. With a two-part DSM-2 within three days, four of the five rungs of the pyro ladder would be committed during the nominal mission with one rung reserved for a contingency situation. Furthermore, consecutive main engine firings must occur no closer than three days apart. With DSM-2 occurring near the spacecraft orbit's aphelion when heliocentric velocity is lowest, and considering that the DSM-2 target is over ten months later at the second Earth flyby perigee, the delta-V cost of splitting DSM-2 into two parts was much less than 1 m/s.

Other reasons for starting DSM-2 with a 100 m/s delta-V trial use of the main engine involve the opportunity to monitor how the spacecraft performs and have time to make changes before the remainder of the maneuver completes three or more days later. If a minor anomaly occurs during DSM-2A execution, there is potential to make a small adjustment to the DSM-2B command sequence – especially if that anomaly was either quickly understood with a clear and testable solution, or if that anomaly was foreseen and already had a resolution tested on a simulator before DSM-2A execution. Examples of such changes between DSM-2A and DSM-2B might involve changes to onboard autonomy settings or limits that define when the spacecraft would enter safe mode during DSM-2B. If a major anomaly occurs during DSM-2A, defined as an anomaly that requires DSM-2B to be delayed, then sufficient propellant margin exists to accommodate a three-week delay to conduct a larger DSM-2C to complete DSM-2 on a re-optimized trajectory with updated target parameters for the December 13, 2024 perigee and all subsequent asteroid encounters and the third Earth flyby. The three-week delayed DSM-2C will be designed, delivered, and tested before DSM-2A as a maximum delta-V contingency case.

Low Delta-V Options to Keep Earth Impact Probability Less Than 1% at EGA 2

The final area where splitting DSM-2 into two maneuvers added operational complexity involved conducting the Monte Carlo analysis required to ensure that any maneuver that directly targets an Earth flyby perigee would result in less than a 1% probability of Earth atmospheric entry/impact. Since the pre-launch 905 m/s DSM-2 and post-launch 816 m/s DSM-2B both have error ellipses many times larger than Earth at the December 13, 2024, Earth arrival such that the probability of Earth impact is less than 0.6% if no TCMs were possible after DSM-2B. The cleanup maneuver after DSM-2 or post-launch DSM-2B will be TCM-10 three weeks later. Prior to launch the TCM-10 target required a 5690 km bias (offset from the optimal perigee target) to keep Earth impact probability under 1% with no post-TCM-10 maneuvers.

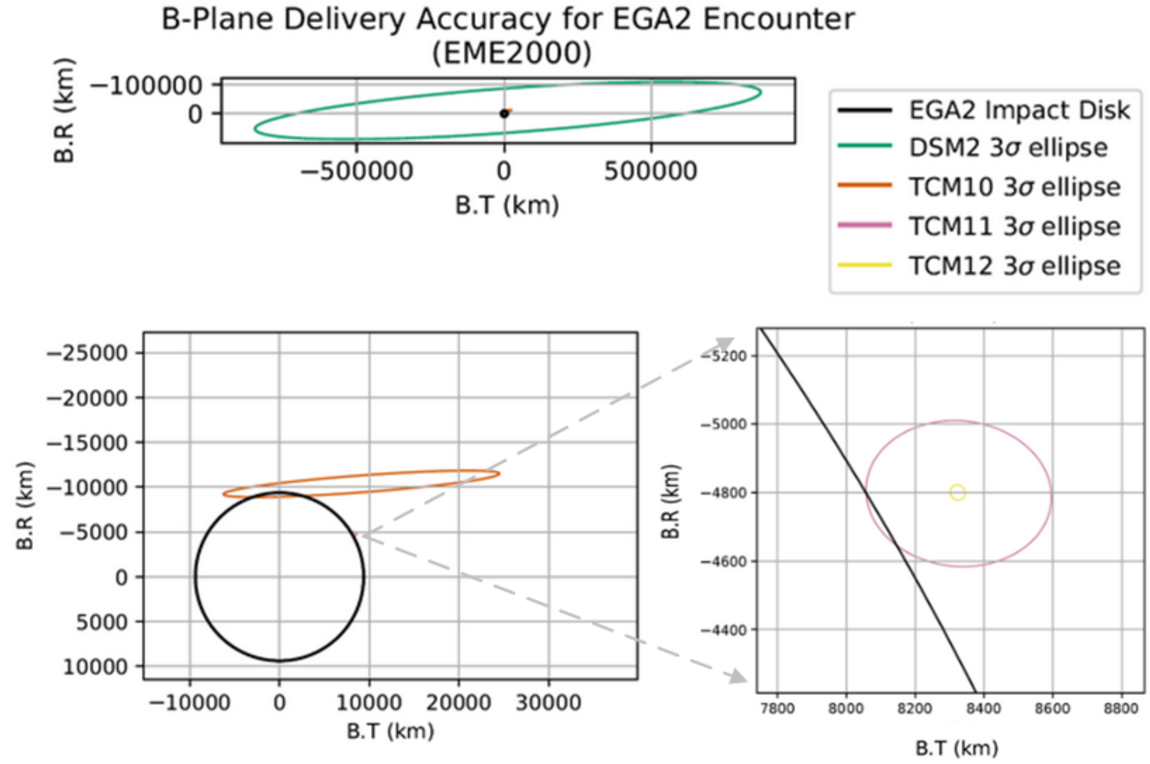


Figure 2. Final Pre-Launch Update of Second Earth Flyby Arrival B-Plane Error Ellipse Projections.

After launch, the Lucy Project added TCM-10a three weeks after TCM-10 as a cleanup for a DSM-2B delayed as late as the TCM-10 date. After launch using a much smaller delta-V TCM-10a as a cleanup for TCM-10 enabled TCM-10a to be the basis for satisfying the Earth impact probability less than 1% requirement. The resulting 1925 km perigee target bias from the optimal target is then applied to DSM-2B, TCM-10, and TCM-10a. This perigee target bias must be removed at the next planned maneuver, which is nominally TCM-11 at 30 days before the second Earth flyby. By adding TCM-10a three weeks after TCM-10, the deterministic TCM-11 delta-V will decrease from 2.3 m/s to 0.8 m/s and the cost of the first post-EGA 2 delta-V ten days after perigee will decrease significantly to near pre-launch levels noted in Table 2. A final pre-EGA 2 cleanup TCM-12 is scheduled for 10 days before perigee if needed. See Figure 2 for the final pre-launch representation of the potential error ellipses from maneuver execution error and orbit uncertainty. The latest post-launch version of Figure 2 is still in work at the time of this paper and will appear in a future paper. The recent addition of TCM-10a is likely to save much more statistical delta-V with the post-EGA 2 cleanup TCM-13 than the 1.4 m/s deterministic delta-V savings as a lower EGA 2 perigee target bias is removed with TCM-11.

MANEUVER PERFORMANCE FROM LAUNCH UNTIL JUST BEFORE DSM-2

The initial measure of Lucy's mission performance is how accurate the launch vehicle delivered the spacecraft onto the initial post-launch targets. Table 4, the final updated version of Table 5 from Geeraert, et. al.[10], shows three independent assessments of the delivery accuracy of the Lucy spacecraft to the launch vehicle target injection point soon after spacecraft separation from the rocket's upper stage. The "Pre-Launch Predict" are the launch vehicle target values. The Orbital Parameters

Message (OPM) results are the estimate of how close the spacecraft came to the target values based on processing on onboard launch vehicle telemetry. The Tracking and Data Relay Satellite System (TDRSS) results are the estimate of the spacecraft target parameters based on this Earth orbiting satellite system's data. The OD003 estimate is from the Navigation team's orbit determination third post-launch solution of the Lucy spacecraft's position and velocity since launch vehicle separation. The sigma values are the 1-sigma uncertainty in the estimated values. Launch energy (C3) is the square of the departure hyperbolic excess velocity along the launch trajectory asymptote. The right ascension and declination of the launch asymptote (RLA and DLA) define the launch escape trajectory direction in the Earth Mean Equator and Equinox of 1 January 2000 (EME2000) reference frame.

Table 4. Lucy Launch Injection Estimates Compared to the Target Values.

Target Parameter	Pre-Launch	OPM		TDRSS		OD003	
	Target	Estimate	Sigma	Estimate	Sigma	Estimate	Sigma
C3 (km^2/s^2)	28.635	28.630	0.093	28.628	0.150	28.632	0.060
RLA (deg)	17.797	17.800	0.041	17.802	0.073	17.795	0.083
DLA (deg)	6.275	6.276	0.018	6.278	0.038	6.278	0.033

After setting the foundation for the mission in the Pre-Launch Mission Plan section and then defining the many post-launch trajectory and maneuver updates in the subsequent three major sections, it's time to assess the results and scope of these post-launch mission changes. The "maneuver performance" referenced in the section title is evaluated not only by viewing the difference between the final reconstructed maneuver performance and the planned maneuver specifications, but also by observing how far the spacecraft differed from the solar system flyby target locations and times that come from updated versions of the optimized full-mission trajectory. Table 1 provides how groups of maneuvers target each flyby of either Earth or one of the many asteroids encountered during the 11.4-year Lucy mission. At the writing of this paper there have been only two primary target events – the first Earth gravity-assist flyby EGA 1 and the post-launch addition of asteroid (152830) Dinkinesh.

As of early January 2024, Lucy successfully completed six course-correction maneuvers, each designed to return the spacecraft to the then-current reference trajectory. The six maneuvers listed in Table 5 are the only course-correction maneuvers executed in the first 27 months after launch. These final reconstructed maneuver performance results do not show *a priori* error estimates because the accuracy of each maneuver has been well below maneuver performance requirements. All TCMs that were planned but not performed were cancelled either because the delta-V was below the minimum 0.03 m/s performance threshold or because trajectory re-optimization would effectively zero out the delta-V cost of a cancelled maneuver. While these results reveal an accurate performance trend, only the last of these TCMs was performed with updated GNC controller onboard software that coordinates thruster pulsing with accelerometer data accounting for the final state of the not fully deployed +Y solar panel. Also note that TCM-08c has higher relative delta-V and thrust direction errors because its delta-V was only twice the minimum allowable TCM delta-V. The first four TCMs cleaned up minimal launch injection error and post-launch outgassing and solar radiation pressure modeling adjustments, as well as targeted the first Earth flyby. The fifth and sixth TCMs targeted the (152830) Dinkinesh flyby. The Earth and (152830) Dinkinesh asteroid encounter target performance results appear in Table 6 with encounter B-plane[11] values expressed in EME2000 and time of closest approach denoted by TCA.

Table 5. Lucy Maneuver Performance Since Launch.

Maneuver Name	Maneuver Start Epoch (UTC)	Duration (s)	Delta-V (m/s)			Pointing Error (deg)
			Design	Estimated	% Difference	
TCM-02a	2 Mar 2022 17:00:00	52.9	1.2520	1.2500	0.16	0.237
TCM-03	7 Jun 2022 17:00:00	103.4	4.2045	4.2018	0.07	0.179
TCM-04	21 Jun 2022 17:00:00	57.5	1.5312	1.5273	0.25	0.448
TCM-04a	3 Aug 2022 17:00:00	16.3	0.4150	0.4151	-0.02	0.249
TCM-08a	9 May 2023 17:00:00	98.5	3.4410	3.4385	0.07	0.269
TCM-08c	29 Sep 2023 17:00:00	3.0	0.0620	0.0608	1.83	1.158

Table 6. Lucy Encounter Target Performance Since Launch.

Encounter Body (Calendar Date)	Parameter	Target	Achieved	Difference
Earth	TCA (UTC)	11:04:26.6	11:04:30.7	+ 4.1 s
(16 Oct 2022)	Radius (km)	6729.45	6737.83	+8.38
	Altitude (km)	352.24	359.73	+7.49
	B.R (km)	5933.95	5931.62	-2.33
	B.T (km)	14086.89	14100.15	+13.26
	Relative Velocity (km/s)	---	12.116	---
Dinkinesh	TCA (UTC)	16:54:36.9	16:54:41.3	+4.4 s
(1 Nov 2023)	Radius (km)	425.00	430.63	+5.63
as of orbit OD051	B.R (km)	64.62	61.20	-3.42
	B.T (km)	420.04	426.26	+6.22
	Relative Velocity (km/s)	---	4.491	---

Trajectory Highlights of the Dinkinesh-Selam Binary Asteroid Encounter

To the surprise of Lucy mission flight operations staff, the flyby images of (152830) Dinkinesh revealed a smaller co-orbital moon. The International Astronomical Union approved the name Selam for this Dinkinesh moon. While shape models are being refined for both objects in this binary system, preliminary estimates of approximate radius of Dinkinesh and each lobe of the contact binary Selam appear in other papers by Geeraert[7] and McFadden[12]. Figure 3 depicts the trajectory, Lucy spacecraft orientation, and images from the Dinkinesh-Selam flyby close-approach phase.

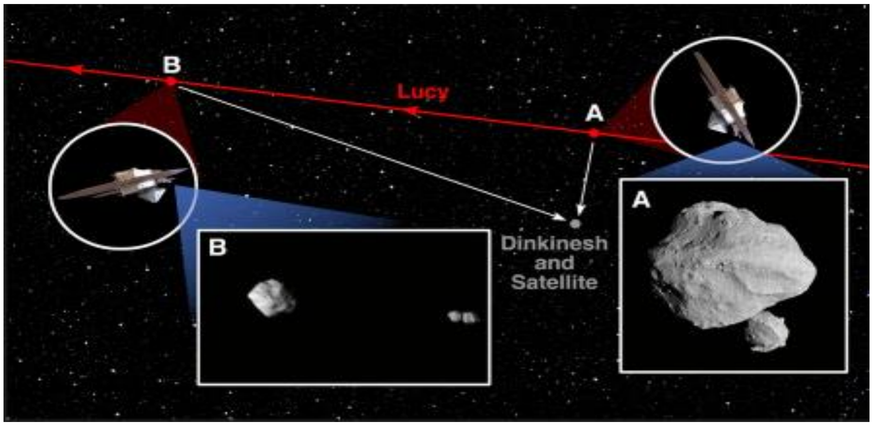


Figure 3. Lucy Trajectory, Orientation, and Sample Images for the Dinkinesh-Selam Encounter.

The Dinkinesh encounter B plane with Lucy location error ellipses (see Figure 4) is close to the final reconstruction on the scale shown. In Figure 4 the black near-circular ellipse denoted by “K” with center coincident with the red “X” for the nominal encounter aim point represents the knowledge limits of where Lucy would be at Dinkinesh closest approach. This K ellipse guided scientists and engineers who planned the flyby image sequences. The “F” final knowledge before the last spacecraft onboard ephemeris update opportunity is represented by the green ellipse and center X. Had any portion of this error ellipse been outside the black K planning knowledge ellipse, the final knowledge OD048 ephemeris would have to be uploaded to the spacecraft to prevent Dinkinesh from being completely or partially absent from image frames. While not required, the OD048 final “F” knowledge ephemeris was uploaded to the spacecraft and Dinkinesh appeared well within every returned image that the onboard terminal tracking camera system[13] expected to see Dinkinesh. The time of closest approach 3-sigma uncertainties were about 18 sec for “K”, 9 sec for “F”, and 0.14 sec for the latest OD051 based flyby reconstruction.

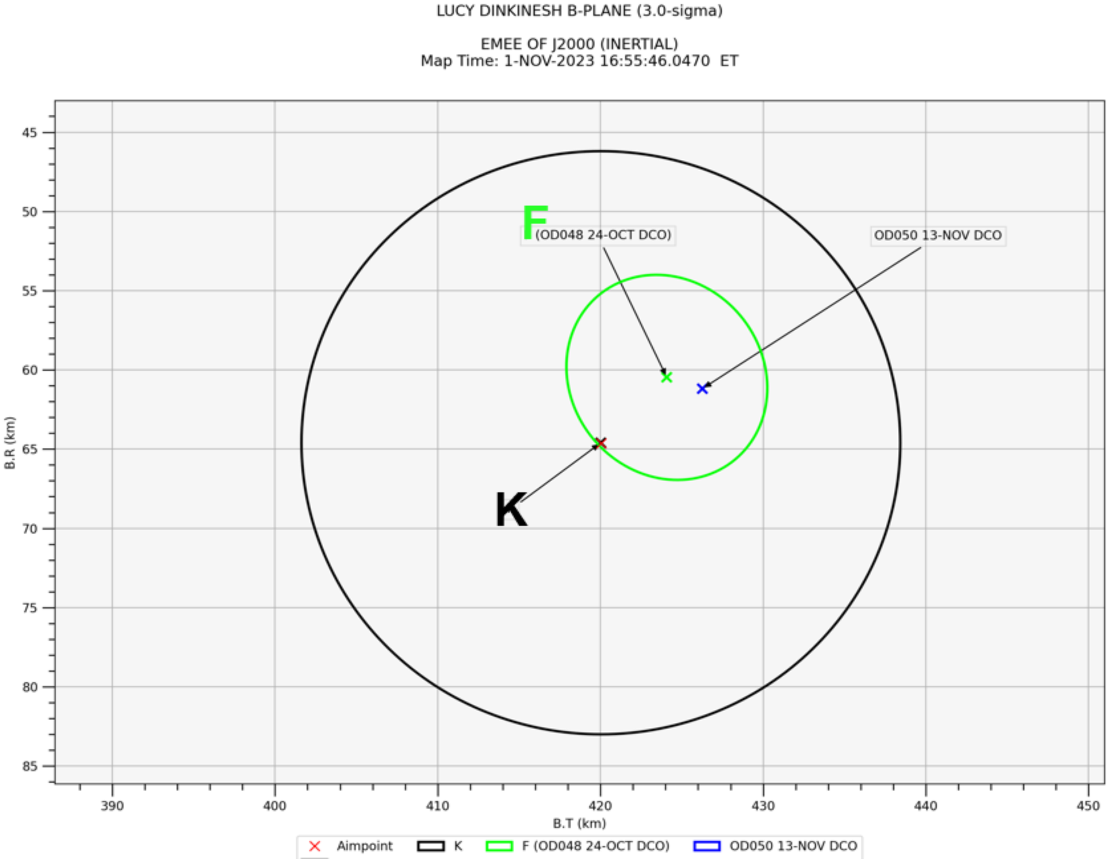


Figure 4. Science Planning Knowledge and Final Pre-Flyby Ephemeris Uncertainties at Dinkinesh.

Current Schedule for DSMs and Flybys

A post-launch representation of all targeted solar system body encounters and DSMs that target those encounters is seen in Figure 5. Note the differences with the final pre-launch timing of encounters and DSMs listed in Table 2. The addition of the Dinkinesh encounter and splitting DSM-2 into two parts are the largest updates. Mission operations and science operations team members requested and received trajectory updates with a higher Earth encounter minimum perigee altitude of 350 km and changes to some asteroid periapsis altitudes. These asteroid closest approach altitude changes include Donaldjohanson from 1000 km to 960 km and Eurybates from 1000 km to 750 km. Any update of the small delta-V deterministic TCMs during the future portion of the full-mission reference trajectory as shown in the Table 2 final pre-launch status would be a less useful reference point since these TCM delta-Vs change with each trajectory re-optimization.

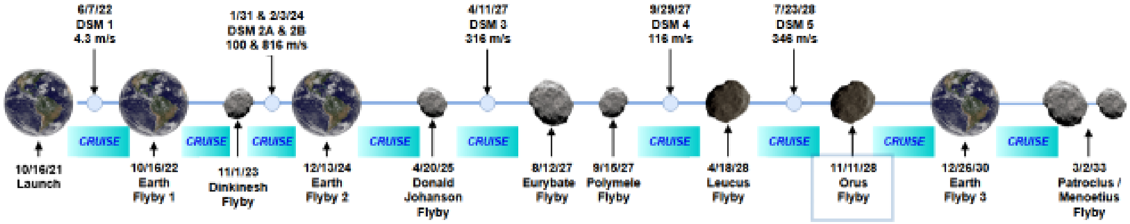


Figure 5. Current Nominal Mission DSM and Encounter Timeline.

CONCLUSION

While many planetary missions make numerous flight plan and objective adjustments during their nominal missions, the Lucy mission successfully made multiple adaptations to enhance spacecraft operational safety and increase returned science all within the first 20% of the nominal mission. With none of these adaptations planned before launch, the flight team elements worked diligently in a professional unified manner guided by an experienced and capable management team.

The primary post-launch mission updates that altered the trajectory and course-correction maneuvers planned originated with the solar array anomaly and resolution, the opportunity to fly by an inner main-belt asteroid at low relative velocity well before the earliest planned asteroid flyby, and lessons learned from the two-part DSM strategy used by the Juno mission. The SAA recovery to a stable spacecraft configuration with one of two large solar panels at least 98% (353° out of 360°) deployed resulted in shifting the minimum perigee altitude constraint from 300 to 350 km for the first two of three Earth flybys. The SAA outcome also combined with Juno Jupiter orbiter precedent to split the mission's largest course-correction maneuver (DSM-2) into two parts three days apart with the first maneuver imparting only 100 m/s delta-V of the total 916 m/s required. For less than 4 m/s extra deterministic delta-V and two new TCMs, mission designers added a November 1, 2023, flyby of what turned out to be a binary Dinkinesh-Selam asteroid system. The addition of a previously unplanned statistical maneuver (TCM-10a) will lower the cost associated with shifting the second Earth flyby perigee target to keep Earth impact probability < 1%.

Early post-launch changes based on science analysis of Trojan encounters required changes in characteristics of several of those asteroid flybys. Two asteroid periapsis ranges were updated from 1000 km to 960 km and 1000 km to 750 km. Most recently, a new requirement arose to adjust Trojan encounter periapsis times such that from acquisition of signal through closest approach through loss of signal (periapsis ± one-way light time to Earth) lies within a single Deep Space Network Earth-based tracking station pass. Three Trojan encounter periapsis epochs were shifted the minimum time, about 2 to 2.6 hours, off the minimum-delta-V times to meet this requirement at the time of planning a full-mission reference trajectory update just before DSM-2. Shifting these encounter times three to four years before they occur adds stability to advance planning phases of encounter science and spacecraft operation command sequences, as well as reduced the total mission delta-V cost of these changes to under 0.5 m/s. The Lucy team adapted to multiple unexpected changes by redesigning the mission to address each change while preserving delta-V margin.

ACKNOWLEDGMENTS

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