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Mission Design and Concept of Operations for the Lucy Mission

Catherine Olkin[1] · Michael Vincent[2] · Coralie Adam[3] · Kevin Berry[4] · Jacob Englander[5] · Sheila Gray[6] · Hal Levison[2] · Julien Salmon[2] · John Spencer[2] · Dale Stanbridge[3] · Brian Sutter[6]

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Abstract
The Lucy mission is NASA's 13th Discovery-class mission and the first mission to the Trojan asteroids. The spacecraft conducts flybys of 8 Trojan asteroids over the course of 12 years. A series of 3 Earth Gravity Assists are used to increase the aphelion of the spacecraft's orbit and to target the final Trojan asteroid flyby. Over the course of 2 years the spacecraft conducts 4 flybys in the L4 swarm to explore 6 Trojan asteroids, which includes two small satellites. Near the end of the mission, Lucy flies past the near-equal size binary, Patroclus-Menoetius, in the L5 swarm. The concept of operations for the Trojan flybys invokes a standard timeline for spacecraft operations to allow a science sequence that is tailored to each Trojan asteroid. The concept of operations enables efficiency of observations and resiliency in the observing sequence to robustly meet the Lucy science requirements.

Keywords Asteroids · Spacecraft · Trajectory design · Space mission

1 Baseline Mission Design

1.1 Overview

The Lucy mission design was developed to provide close flyby observational opportunities of a diverse population of Jupiter Trojan asteroids. A 6-year resonant orbit, essentially a Jupiter Trojan cycler, with apoapsis ranges slightly above 5 AU, and periapsis ranges of slightly less than 1 AU, was adopted as the baseline skeleton profile from which the targeting of specific Trojans could advance.

✉ C. Olkin

1 Muon Space, Mountain View, CA, USA

2 Southwest Research Institute, Boulder, CO, USA

3 KinetX, Simi Valley, CA, USA

4 NASA Goddard Spaceflight Center, Greenbelt, MD, USA

5 Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA

6 Lockheed Martin, Littleton, CO, USA

Using the resonant orbit constraint, an initial set of targets chosen for their spectral and mass diversity was reduced to flybys of (3548) Eurybates, (21900) Orus in the L4 swarm, and (614) Patroclus/Menoetius in the L5 swarm with Earth flybys in December of 2024 and 2030. A search for additional targets that were in close proximity to the nominal trajectory was undertaken resulting in the inclusion of (15094) Polymele and (11351) Leucus to the L4 observations. In a similar manner, opportunities to observe a main belt asteroids to exercise the flight system and ground system prior to the L4 encounters were evaluated and resulted in the inclusion of (52246) Donaldjohanson and (152830) Dinkinesh.

Having designed the heliocentric Trojan encounter orbits, the task of attaching that orbit with a December 2024 EGA to a 2021 launch opportunity as required by the Discovery program Announcement of Opportunity commenced. Following a significant optimization undertaking, the design of a series of orbits that enabled both a 21-day launch period and a single heliocentric Trojan encounter profile was developed. This strategy placed the Lucy spacecraft onto the identical heliocentric trajectory following the 2nd Earth gravity assist regardless of launch date. This capability allows the spacecraft, operations, and science to focus their efforts on a sequence of very specific encounter characteristics with minimal variability.

This general mission architecture has essentially remained unchanged since selection (Fig. 1), allowing the Lucy spacecraft, instrumentation, and operations to advance in a linear fashion through the development cycles with minimal redesign due to mission changes.

The first encounter is a flight test of the system with the main belt asteroid Dinkinesh on November 1, 2023; the second encounter is with Donaldjohanson in April 2025. The early timing of these two encounters gives the operations team time to fully address any unexpected behavior prior to the first L4 Trojan encounter.

The Eurybates encounter on August 12 of 2027 has been enhanced by the discovery of a moon, Queta, orbiting the large Trojan (Noll et al. 2020; Brown et al. 2021). About 1 month later, a flyby of Polymele and its recently discovered satellite will be performed on September 15, 2027. Flybys of Leucus on April 18, 2028 and Orus on November 11, 2028 will conclude the L4 Trojan encounters.

Small deterministic Deep Space Maneuvers (DSM) and smaller Trajectory Correction Maneuvers (TCM) will be performed to encounter each object at the proper lighting and distance requirements. Lucy will flyby Earth on December 26, 2030 and use it to adjust the trajectory to encounter the near equal size binary pair of Patroclus/Menoetius on March 3, 2033. The mission is completed after transmission of the data following the Patroclus/Menoetius encounter, however Lucy will remain on its stable Trojan cycler orbit and return to the L4 and L5 swarms repeatedly over the next few million years.

1.2 Launch

Lucy launched on an Atlas V 401 with a Centaur upper stage, provided by United Launch Alliance (ULA). The launch mission design team was tightly integrated among GSFC, KinetX, Lockheed-Martin, the Launch Services Program (LSP) at KSC, and ULA. Lucy was designed with a primary launch period in 2021 and a backup in 2022. The primary launch period consisted of 23 daily launch windows, each approximately 60 minutes long, beginning on October 16th, 2021. The 2022 launch period was constructed by removing Earth gravity assist (EGA) 1 from the mission design and launching on any of 17 days surrounding the date corresponding to EGA1 in the nominal design.

Because Lucy visits ten small bodies in one mission, small changes in the launch mission design drive changes to the entire mission. However, it was not possible to formulate

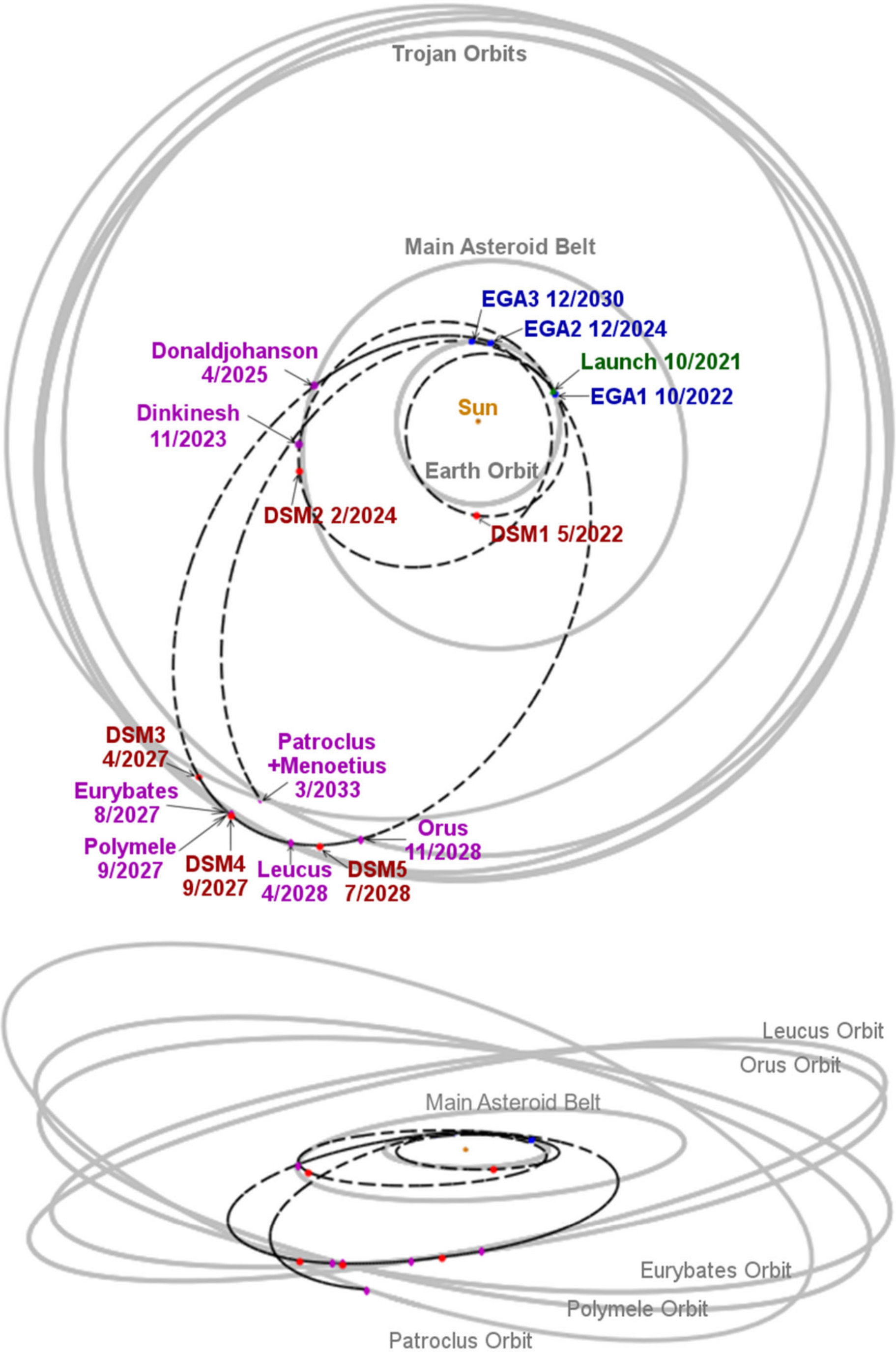

Fig. 1 The Lucy trajectory (black dashed line) and the orbits of Earth, the Main Belt Asteroid Donaldjohanson and the Lucy Trojan targets (gray solid lines) as seen from two different perspectives, a, and b

the entire mission design from the launch pad to Patroclus-Menoetius (PM) as a single optimization problem because there is no optimization software package that can properly model launch, atmospheric flight, and interplanetary flight. The Lucy team therefore chose to use the Evolutionary Mission Trajectory Generator (EMTG; Englander and Ellison 2020) to optimize the interplanetary trajectory and ULAs Spartan software to model the launch, with both tools modeling the hyperbolic injection maneuver.

The trajectory optimization was done in three stages. In the first stage, before ULA was selected as the launch partner, the mission was optimized entirely in EMTG and the launch vehicles ascent to the parking orbit was not modeled. Instead, the parking orbit was approximated as a circle with 28.5 degree inclination and passing over KSC. The injection burn was modeled as an impulse. EMTG was used to optimize the timing of this impulse, the right ascension of the ascending node of the parking orbit, and then the entire Lucy mission all the way to PM ten years later. This approach was sufficient to generate an initial set of launch targets twice the hyperbolic excess energy (C3), right ascension of the launch asymptote (RLA) and declination of the launch asymptote (DLA) for a single opportunity in each of 21 days, and to provide an optimized ΔV budget that changed by less than 1% in later iterations.

Once ULA joined the team, a second iteration was done to a higher level of fidelity. ULA generated optimal ascent trajectories to meet the launch targets for each of the 21 days, and generated Trajectory Interface Point (TIP) states for each launch opportunity. TIP takes place 20 minutes after the injection burn is completed and includes the small delta-v caused by the separation mechanism. GSFC then re-optimized the entire mission-to-go using EMTG. Since the original estimate of TIP time by GSFC in the first iteration was less accurate than the high-fidelity modeling of TIP by ULA, this resulted in an outbound trajectory that was sub-optimal. The TIP epoch mismatch of 20 minutes resulted in designs with 5 m/s of deterministic v at TCM-1, 30 days after launch.

The design process changed in the third iteration, both to remove the deterministic TCM-1 and to accommodate a new constraint that Lucy may not operate the main propulsion system closer than 0.89 AU to the Sun. The third iteration was similar to the second except that instead of re-optimizing the mission-to-go from the ULA-provided TIP state, GSFC used the parking orbit design from ULAs launch optimization as an initial condition for a larger optimization problem that included a finite burn model of the injection and then the rest of the mission all the way to PM. At this time an additional two days were added to the launch period, resulting in 23 opportunities. EMTG varied the initial epoch and duration of the injection maneuver but the direction was fixed along the velocity vector. New launch targets were harvested from this design and passed back to ULA. ULA performed a final round of launch trajectory optimization and provided new TIP epochs and states, which this time were within 17 seconds of the EMTG solution. A final round of EMTG optimization was performed using the TIPs as an initial condition, resulting in a reduction of TCM-1 to 1 m/s at the center of each daily window. The final targets are shown in Fig. 2.

ULA then generated optimized launch trajectories to the final target set for every five minutes within a two hour window centered on each days optimal time. This resulted in 575 TIP states and epochs, each of which was used to optimize an interplanetary trajectory. ULA also provided 7x7 Injection Covariance Matrices (ICMs) for each TIP. The Lucy navigation team at KinetX then rendered the entire post-launch trajectory and performed a statistical analysis in the MIRAGE-PIRATE (Knittel et al. 2019) toolchain using the TIP states and ICMs as an initial condition and the EMTG trajectory to provide targets.

Lucy launched on October 16th, 2021, at the first opportunity in the available window. The delivery was incredibly accurate, achieving the targeted C3 to within 0.003 km^2/s^2, RLA

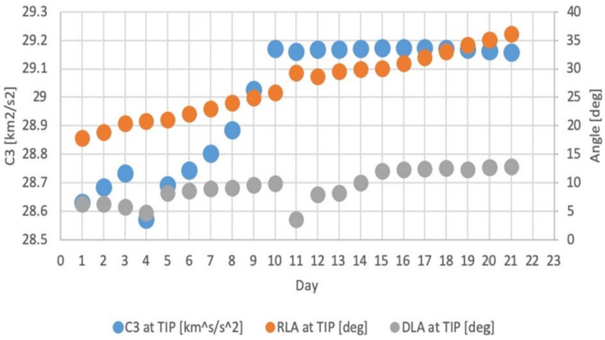

Fig. 2 C3, RLA, and DLA across 23 launch opportunities from October 16, 2021 to November 7, 2021

within 0.002 deg, and DLA within 0.003 deg. As a result, we were able to cancel the first two trajectory correction maneuvers that had been scheduled for November and December of 2021.

1.3 Earth Gravity Assist 1

The pre-launch trajectory optimization found that the optimal date for the first Earth Gravity Assist (EGA1) was one year after launch. Since Lucy launched on the first day of the launch window, October 16, 2021, EGA1 occurred on October 16, 2022. The post launch cruise trajectory placed Lucy into a heliocentric orbit with an initially increasing solar range, reaching a maximum of 1.16 AU before dropping to a minimum of 0.835 AU. The purpose of EGA-1 was to increase the energy of the orbit by raising the semi-major axis, increasing the orbit period to roughly two years with a maximum solar range of 2.3 AU and a minimum solar range of 0.86 AU. If Lucy had been unable to launch within our primary launch period, then the backup launch opportunity one year later would have eliminated the need for EGA1 entirely, at the cost of spacecraft mass. Figure 3 shows the EGA-1 flyby trajectory relative to the Earth.

A maneuver schedule for the launch – EGA1 timeframe was designed before launch, consisting of one deterministic deep space maneuver (DSM) and six statistical trajectory correction maneuvers (TCM's), to correct for errors in launch injection, orbit determination and trajectory prediction, and maneuver execution. The term 'deterministic' is reserved for maneuvers required in the reference trajectory assuming no errors in orbit determination, trajectory prediction or maneuver execution, hence DSM's are deterministic maneuvers. The term TCM is typically reserved for maneuvers which correct for the statistical errors. However, to avoid confusion for operations, DSM's are also given a TCM number so that propulsive maneuvers can be tracked in a continuous fashion.

The Lucy spacecraft has two propulsive maneuver modes, hydrazine trajectory correction maneuver (TCM) thrusters for maneuvers under 50 m/s, and a bi-propellant main engine (ME) for maneuvers over 50 m/s. Nominally, only one deterministic deep space maneuver (DSM) was required for the Launch to EGA-1 phase which was planned a little over six months after launch, with a delta-v of about 6.5 m/s in the pre-launch optimized trajectory. Hence DSM-1 was executed using the TCM thrusters.

TCM's 1 and 2 were planned to correct for launch injection errors at 30 and 60 days after launch. TCM-2a was added post-launch to test the propulstion system. DSM-1, was required to keep Lucy on the optimized trajectory and to target the updated EGA-1 aimpoint based on a trajectory reoptimization. TCM-4 was added to correct for any potential DSM-1 maneuver execution error. Finally, TCM's 5 and 6 were added at 30 and 10 days prior to

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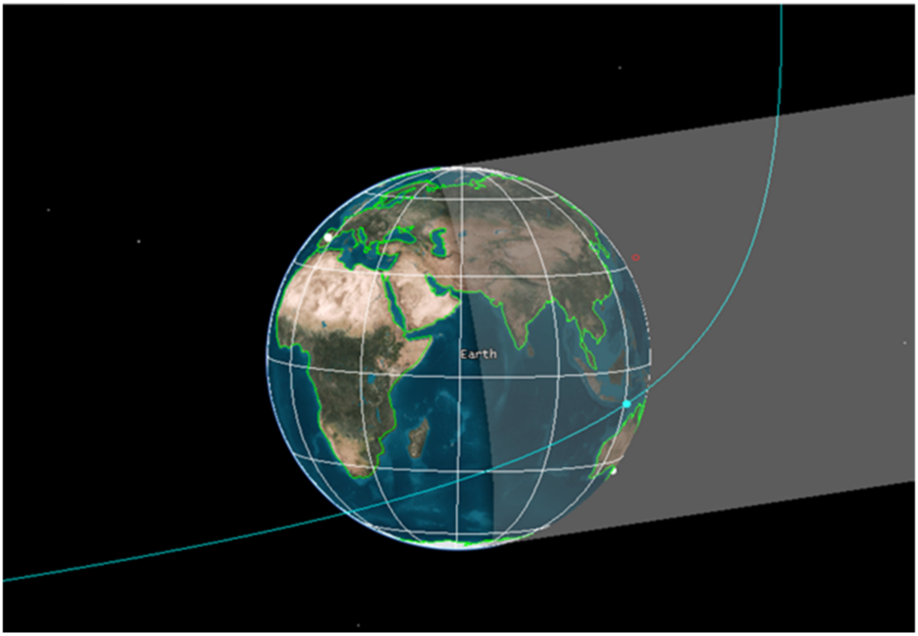

Fig. 3 The Lucy trajectory during EGA1. This for the opening of the launch period

the encounter to target the EGA encounter target in the B-plane and correct for OD and trajectory prediction errors. A potential collision avoidance maneuver one day prior to the encounter (TCM-6a) was added should the Conjunction Assessment Risk Analysis (CARA) team determine that the probability of collision (Pc) during the Earth encounter exceed 1 in 10,000. Finally, TCM's 7 and 8 were added to correct for errors in the Earth flyby modeling. The maneuver schedule is given in Table 1.

To ensure that at no point in the launch to EGA-1 cruise phase the probability of Earth impact or atmospheric entry is less than 1% should no additional maneuvers be performed, a progressive targeting strategy was employed walking in the perigee altitude. This was done by first optimizing the trajectory, then performing a statistical maneuver (Monte Carlo) analysis incorporating predicted orbit determination (OD) errors from an OD covariance analysis, and maneuver execution errors provided by the GNC (Guidance, Navigation and Control) team, to determine the impact probability for each subsequent maneuver. If it was found that the impact probability was less than 1%, a new trajectory optimization was performed with a higher perigee altitude constraint, and the Monte Carlo analysis was performed again. This iteration continued until the overall mission delta-v was minimized while satisfying the 1% constraint. Figure 4 shows the as-flown B-plane targeting history from launch to EGA_1.

Once TCM-4a was executed, the reference trajectory used for the maneuver design, based on OD016, was held fixed and no further reoptimizations were adopted, although they continued to be performed and tracked to determine whether TCM's 5 and 6 would need to be executed. There was some drift in the trajectory compared to the reference trajectory during the approach, but the trajectory optimization showed that these small errors could be absorbed in post-EGA-1 maneuvers.

Figure 5 shows the approach B-plane history following TCM-4a. The red X indicates the target. Some drift was observed on the approach, increasing the periapsis distance by around

Table 1 Lucy Launch to EGA-1 Maneuver Schedule

Maneuver	Date	Delta-V (m/s)	Purpose
Launch	Oct 16, 2021	N/A	Explore the Jupiter Trojans!
TCM-1	Nov 15, 2021	Cancelled	Correct for launch injection error
TCM-2	Dec 15, 2021	Cancelled	Correct for launch injection error
TCM-2a	Mar 2, 2022	1.252	Propulsion system test
			Target 80,915 km EGA altitude
DSM-1 / TCM-3	June 7, 2022	4.204	15.8% radial EGA aimpoint bias
			Target 2,187 km EGA altitude
TCM-4	June 21, 2022	1.531	13.0% radial EGA aimpoint bias
			Target 1,861 km EGA altitude
TCM-4a	Aug 3, 2022	0.415	Un-biased EGA aimpoint
			Target 350 km altitude
TCM-5	Sep 16, 2022	Cancelled	EGA-1 targeting
TCM-6	Oct 6, 2022	Cancelled	EGA-1 targeting
TCM-6a	Oct 15, 2022	Cancelled	Collision avoidance maneuver
TCM-7	EGA + 10 days	Cancelled	Correct for EGA error
TCM-8	EGA + 30 days	Cancelled	Correct for EGA error

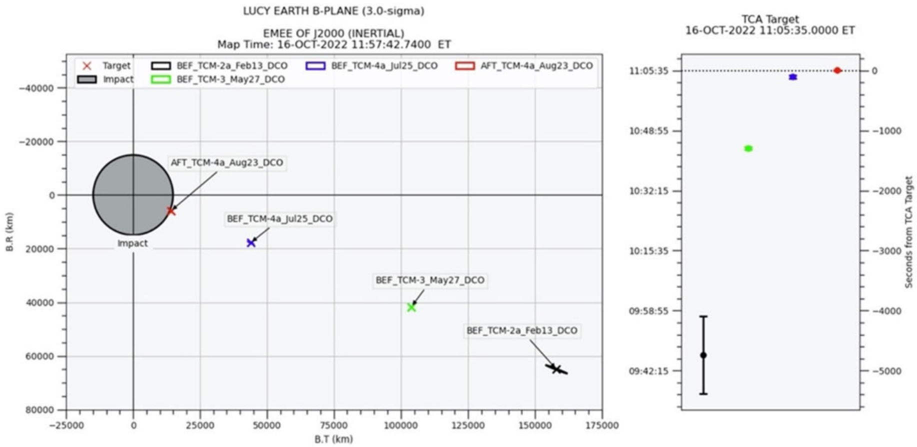

Fig. 4 EGA B-plane Aimpoint History

10 km, but this was deemed a positive occurrence by the GNC team as it reduced aerodynamic torques on Lucy's very large solar arrays. Since there was a negligible delta-v penalty and a benefit to the spacecraft, TCM's 5 and 6 were cancelled. This eliminated the need to perform TCM's 5 and 6, also retiring the risk associated with executing propulsive maneuvers close to the flyby during a period of high spacecraft activity. The final, reconstructed B-plane intercept is shown in Fig. 5,

A final collision avoidance maneuver was prepared and ready to be executed 12 hours prior to perigee to adjust the time of perigee passage should the need arise. The Lucy project coordinated with the CARA team at GSFC to determine if such a maneuver was needed to

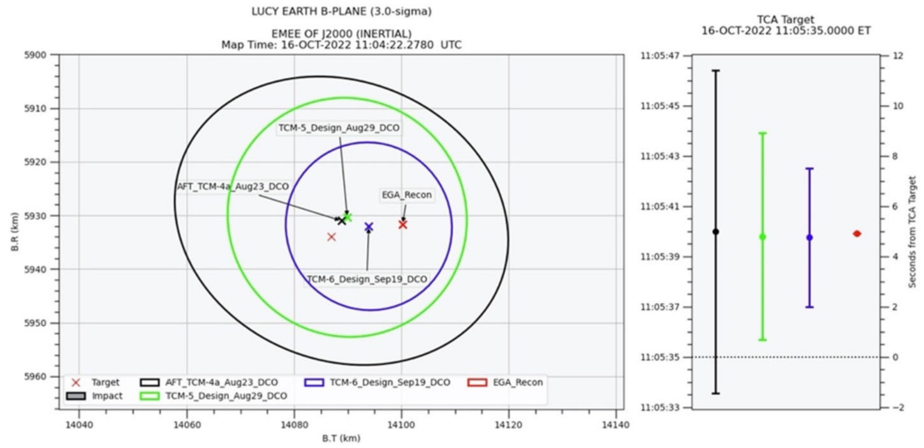

Fig. 5 Lucy B-plane History After TCM-4a

Table 2 EGA-1 B-plane Accuracy (EME2000)

Trajectory	B.R (km)	B.T (km)	Periapsis time (UTC)
Reference Trajectory	5933.946	14,086.887	16-OCT-2022 11:04:26.564
EGA Reconstruction	5931.616	14,100.149	16-OCT-2022 11:04:30.750
Difference	−2.33	13.262	4.186 s

avoid a possible collision with any other objects in the space catalog. The navigation team provided the CARA team trajectories and associated uncertainties, beginning 7 days prior to launch. The CARA team had three categories of risk: low risk with $P_c < 1e\text{-}7$, medium risk with $1e\text{-}4 > P_c > 1e\text{-}7$, and finally high risk if $P_c > 1e\text{-}4$. In the event that it had been necessary to maneuver, two "pre-canned" maneuvers were prepared in advance to change the time of perigee, arriving either two or four seconds earlier, which were also assessed by the CARA team. If necessary, the lowest risk trajectory would have been chosen 24 hours before perigee and a diversion maneuver would have been executed 12 hours later. Lucy was fortunate in that no objects were within the high or medium risk categories, so a decision was made not to execute TCM-6a.

EGA1 provided an opportunity for unique in-flight instrument calibration activities using the Earth and Moon on approach and departure. The alignment with the Earth, Moon, and Sun was favorable on trajectories that launch in the beginning of the launch period, but not in the later portion of the launch period, so it was fortuitous that Lucy able to launch on the first day.

The last propulsive maneuver executed was 54 days prior to the EGA. In this time period, there were daily momentum wheel desaturation maneuvers and a relatively large solar radiation pressure perturbation due to the large size of the solar arrays, which was challenging to model. Table 2 shows the reference trajectory B-plane intercept used for targeting and final reconstructed B-plane from post-EGA orbit determination.

EGA1 also provided an opportunity for unique in-flight instrument calibration activities using the Earth and Moon on approach and departure (see chapter by Spencer et al.).

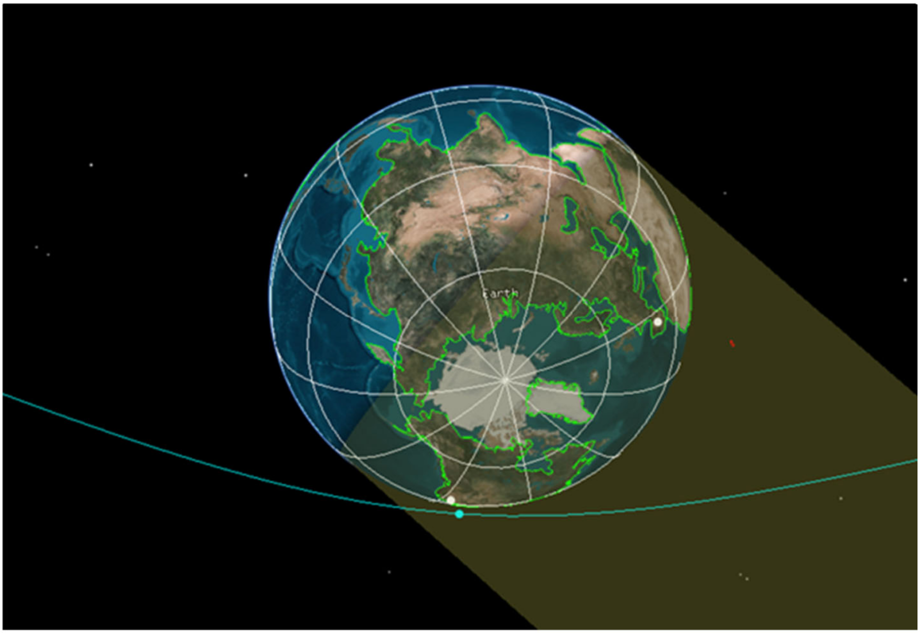

Fig. 6 The Lucy trajectory during EGA2 for launch at the opening of the launch period

1.4 Earth Gravity Assist 2

The second Earth Gravity Assist (EGA2; Fig. 6) occurs on December 13, 2024, which is approximately two years after EGA1. Roughly half way in between EGA1 and EGA2, the second Deep Space Maneuver (DSM-2) is performed to set up the proper Earth flyby conditions at EGA2 to encounter the main belt asteroid Donaldjohanson. DSM-2 will be performed on the bipropellant main engine and is the largest maneuver of the mission with a ΔV magnitude between 760 m/s and 912 m/s (depending on launch date). Due to the size of DSM-2 and the long duration until EGA2, the perigee target will not need to be biased. The EGA2 B-Plane uncertainty at the time of DSM-2 is so large that the probability of Earth impact or atmospheric entry is always smaller than 1%. The subsequent TCMs occurring 30 days and 7 days before EGA2 will bias the perigee target as-needed to ensure that the spacecraft is never on an Earth intercept trajectory.

EGA2 has a nominal perigee altitude ranging from 350 km at the open of the launch period to 580 km at the close of the launch period, with an eclipse duration of about 20 minutes. This gravity assist further increases the semimajor axis of Lucys heliocentric orbit, increasing the orbit period to roughly six years. Similar to EGA1, the Navigation team will coordinate with CARA to assess the need of a collision avoidance maneuver and execute it if necessary.

1.5 Dinkinesh and Donaldjohanson Encounter

The first two encounter for Lucy are both flight tests before encountering the Trojan asteroids. There are no science requirements to accomplish at either of these encounters, although scientific data will be collected. This rehearsal will reduce risks for the Trojan flybys by exercising the system in flight. The closest approach distance to Dinkinesh is 425 $\pm$ 6 km and for Donaldjohanson it is nominally 1000 km to have a similar angular rate at the flyby for our most pressing case, Polymele.

On April 20, 2025, the Lucy spacecraft will flyby the Main Belt Asteroid (52246) Donaldjohanson (DJ) on the way out to the L4 swarm of Trojan asteroids.

As part of the rehearsals, the on-board terminal tracking will be taking data with the Terminal Tracking Camera (T2Cam) and the state estimation will be computing the asteroid target location. The priority is to establish state estimation is working properly and it is not required to enable terminal tracking (using the estimated state to point the Instrument Pointing Platform).

The rehearsal will also exercise the navigation TCM process, and the ability to estimate planetary ephemerides, and that of the spacecraft relative to the flyby targets, using radiometric data types and optical navigation images using the LLORRI instruments supplemented by images from T2Cam. Radiometric data types will be collected as well as optical navigation images using the L'LORRI instrument. There will be two TCMs to target the delivery of the spacecraft to the aim point, one 30 days before closest approach and one 7 days before closest approach. The knowledge update process will also be exercised in the rehearsal where the post-TCM spacecraft and the flyby target ephemerides are sent to the spacecraft 4 days prior to the encounter.

Even though there are no science requirements tied to the encounters, both asteroids are interesting scientific targets. Dinkinesh will be the smallest main belt asteroid to be visited by a spacecraft, extending the detailed knowledge of asteroid surface properties to a smaller size regime.

Donaldjohanson is a member of a young collisional family (Nesvorný et al. 2015) and will be the first collisional family member visited by spacecraft. Science data will be collected during approach to DJ. On approach the phase angle is 15° and, therefore, on departure if the instruments were pointing at DJ they would be pointing near the Sun. For the health and safety of the instruments, the Instrument Pointing Platform will point away from DJ to a location that ensures it will not point within 40 deg of the Sun.

1.6 L4 Trojan Encounters

The Lucy mission will conduct 4 flybys of 6 Trojan asteroids in the L4 swarm. For each of these encounters the closest approach distance was chosen to accomplish the Level 1 science objectives (Olkin et al. 2021b). The nominal closest approach distance is 1000 km from the center of the Trojan asteroid on the sunward side (Table 3). This distance is close enough to meet our mass determination requirement of 25% for Eurybates, Leucus and Orus, but not Polymele, the smallest of our required targets (Levison et al. 2021). The closest approach distance will be re-evaluated prior to building the final encounter sequence and could be revised. The Polymele encounter has a nominal closest approach distance of 434 km. All the Trojan encounters meet all science requirements for closest approach distances that are about 3σ from the aim point.

The spacecraft approaches each of the Trojan asteroids in the L4 swarm from a solar phase angle between 82° to 126° (see Table 3). The spacecraft will pass on the sunward side of the Trojan asteroid, therefore, the phase angles will decrease leading up to closest approach. The decreasing phase angle corresponds to increasing illuminated surface area for shapes that are not pathological (spherical, oblate, top shaped).

The velocity in Table 3 is relative to the Trojan asteroids. At these velocities and closest approach distances, the spacecraft sweeps through phase angles from 75° to 0° in $\sim$3 minutes.

Table 3 Encounter Circumstances

Encounter	Date	Ph. ang. deg	C/A dist km	Velocity km/s	Earth range AU	Sun range AU
Eurybates	08/12/2027	81	1000	5.7	5.6	5.7
Polymele	09/15/2027	82	434	6.0	6.2	5.7
Leucus	04/18/2028	104	1000	5.9	4.9	5.7
Orus	11/11/2028	126	1000	7.1	6.2	5.3

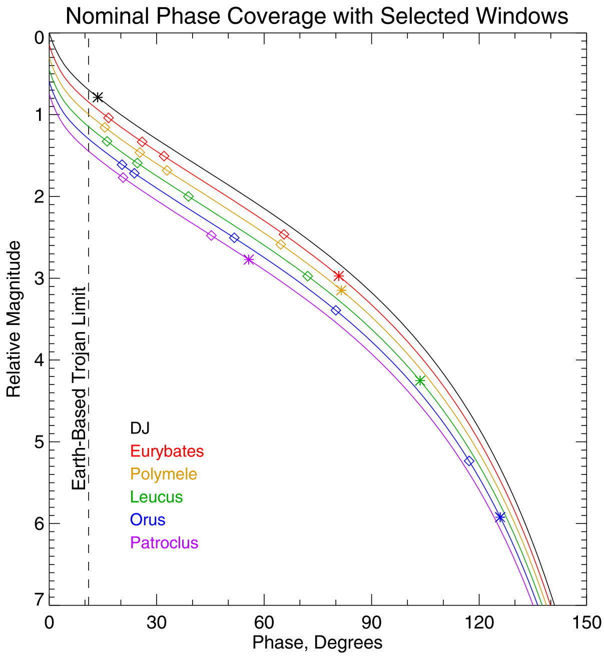

Fig. 7 The relative magnitude as a function of phase angle for each of the Trojan asteroids and the Lucy Main Belt Asteroid flyby target. Each of the asteroids is offset for readability. The maximum phase angle observable from Earth is indicated by a dashed line. The phase angle on approach to the flyby is denoted by a *. Lucy will nominally observe the Trojan asteroids at the phase angles indicated by the diamonds to build up knowledge of the phase curve of the Trojans before encounters

The closest approach distance for Queta, the small moon of Eurybates, is uncertain at this time because of the uncertainty in its orbital parameters (see chapter by Noll et al.).

From Earth, the Trojan asteroids cannot be observed at a phase angle of more than 11°, therefore, observations of the Trojan asteroids at moderate phase angles are planned well in advance of the Trojan encounters to inform estimates of expected brightness and exposure times. The strawman plan for photometric observations of our targets is shown in Fig. 7.

The Navigation team will use radiometric data types and optical navigation to deliver the spacecraft to the aim point. The B-plane delivery uncertainty in the closest approach distance will be no greater than 75 km (3σ) and the knowledge of the spacecraft location relative to the Trojan asteroid at 4 days before closest approach will be less than 100 seconds (3σ) in the time of flight direction, and 50 km (3σ) in each of the radial and cross track directions. For Polymele, the requirement on the delivery uncertainty to the aim point is reduced to 40 km to achieve the mass determination objective.

In order to deliver the spacecraft to the aim point, there are a series of TCMs. The first of these occurs at E-30 days (30 days before closest approach). The next occurs at E-7 days. Each of these TCMs has a data cut off 3 days before the maneuver execution. For the knowledge update at E-4 days, there is a data cutoff at E-5 days.

1.7 Earth Gravity Assist 3

The third Earth Gravity Assist (EGA3) occurs on December 27, 2030, which is approximately two years after the Orus encounter. However, the maneuver that targets EGA3 is the fifth Deep Space Maneuver (DSM-5), which occurs on July 23, 2028 (nearly 4 months before the Orus encounter). At roughly 350 m/s, DSM-5 targets the Orus encounter and sets up the proper Earth flyby conditions at EGA3 to encounter the Patroclus/Menoetius binary system in March of 2033 at a specific time where both targets will be observable but not overlapping from the spacecraft's perspective. Unlike the previous EGAs, the nominal EGA3 perigee target results in a 1% probability of Earth impact or atmospheric entry, so biasing will not be necessary in the design of DSM5 or any of the subsequent TCMs.

EGA3 is similar to EGA1 and EGA2, but with a flyby altitude of 600 km and an eclipse duration of 11 minutes. This gravity assist will change the heliocentric orbit inclination by nearly 9 degrees from 1.83 to 10.75. The Navigation team will coordinate with CARA to assess the need of a collision avoidance maneuver and execute it if necessary.

The TCMs preceding and following EGA3 are also used to correct any errors in the timing of the Patroclus/Menoetius binary encounter. To provide the best possible observations of both Trojan asteroids, arrival at the system will be timed to minimize the angular displacement of the two bodies without any overlap during the approach. This improves the terminal tracking solution by increasing the time that the two targets are in the T2Cam field of view. Patroclus and Menoetius have an orbital period of about 4.28 days about their gravitational center, hence this geometry also repeats every 4.28 days. The selection of the current encounter date and time is a reflection of the current understanding of the ephemeris of the two objects. It should be noted that the uncertainty in this ephemeris propagated 15 years into the future means this date is merely a design point that will be determined with more confidence as time passes by.

1.8 L5 Trojan Encounter

The Lucy spacecraft will fly past the near equal size binary pair Patroclus and Menoetius (otherwise known as the Patroclus-Menoetius binary, PMB) in the L5 swarm of Trojan asteroids. The closest approach will occur in March 2033. The exact day and time for the flyby will be determined by the time of the Deep Space Manuever (DSM-5) that sets up the geometry for Lucy's third Earth Gravity Assist (Dec. 2030) which targets the PMB encounter. DSM5 occurs after the Leucus encounter and before the Orus encounter. This is roughly between April and November 2028. The timing of the PMB encounter is critical because there are constraints on the relative locations of Patroclus and Menoetius. As the spacecraft is approaching Patroclus and Menoetius, the two objects should not be aligned as seen by the spacecraft or illuminated terrain would be unobservable. Additionally, there is limited range of motion of the gimbal in the direction that points the instrument pointing platform in the direction out of plane of the encounter (the encounter plane is composed of the velocity vector of the spacecraft and the vector from the spacecraft to the Trojan asteroid at closest approach). The instrument pointing platform can point $+9$ deg to -15 deg out of plane, therefore, limiting the out of plane distance Patroclus can be from Menoetius in the out of plane direction.

The Lucy spacecraft will fly past Menoetius before Patroclus. The encounter aim point will be defined relative to Menoetius. Currently the aim point for the Menoetius encounter is planned to be 1075 km from the center of Menoetius and on the sunward side. This puts the closest approach distance to Patroclus at 1245 km for our nominal encounter on March 3, 2033. On approach to the PMB, the phase angle will be 56 deg and the encounter velocity is 8.8 km/s with a Earth range of 5.2 AU and a Sun range of 5.4 AU.

The B-plane uncertainties and knowledge requirements are the same as described for the L4 Trojan asteroid targets.

After prime mission, Lucy will continue flying through the L4 and L5 swarms.

2 Trojan Encounter Concept of Operations

2.1 Encounter Architecture

The Concept of Operations for the Trojan flybys share many of the same elements, but there are modifications for each encounter. This section will describe the common elements across encounters and later sections will highlight some of the modifications made for specific encounters.

2.1.1 Baseline Timeline

For each of the Trojan encounters there is a baseline of activities that are common across encounters. Figure 8 shows selected common elements near closest approach. The L'LORRI instrument is turned on at E-60 days; L'Ralph is powered on at E-12 days; L'TES and the Terminal Tracking cameras are powered on at E-6 days. The first observations as part of the Trojan flyby occur at E-60 days with optical navigation to support ECM1 (Encounter Correction Maneuver) at E-30 days. Science observations begin at E-12 days and continue in general to E+20 days. The sequence of science observations for individual targets will have many commonalities with others, but will also incorporate unique aspects that depends on target specific parameters. The final planned TCM to refine the encounter trajectory occurs at E-7 days with an opportunity at E-5 days for a contingency TCM if needed. At E-4 days, auto-recovery mode is enabled. If a fault occurs when autorecovery is enabled (from E-4 days to E+4 days), the fault protection software will try to resolve the fault and rejoin the science sequence. Also, at E-4 days, the Final Knowledge Update is uploaded to the spacecraft and includes the best known ephemeris of the Trojan asteroid target along with other configuration files.

A unique aspect of the Lucy mission is that near closest approach science observations are initiated based on range to the target rather than time. This is commanded using the Trojan Event File (TEF) starting at E-4 days. The TEF is a series of observation in virtual machine language (VML) blocks (Grasso and Lock 2008) and their parameters ordered by range to the target. The range to the target is determined initially from an on-board ephemeris. When the terminal tracking is enabled, the range to the target is determined from the state estimation of the terminal tracking. At a later time, designated in the command sequence, the position of the IPP is driven by the state estimation solution. The reason the Lucy mission uses range-based observations is to ensure observations are taken with the desired resolution to accomplish the science objectives. The state estimation will cause a fluctuation in the time a given range is achieved compared to the on-board ephemeris or even a previous estimate of the state. This fluctuation could, in principle, result in a command needing to be executed before the previous one has completed. This is problematic for observations with

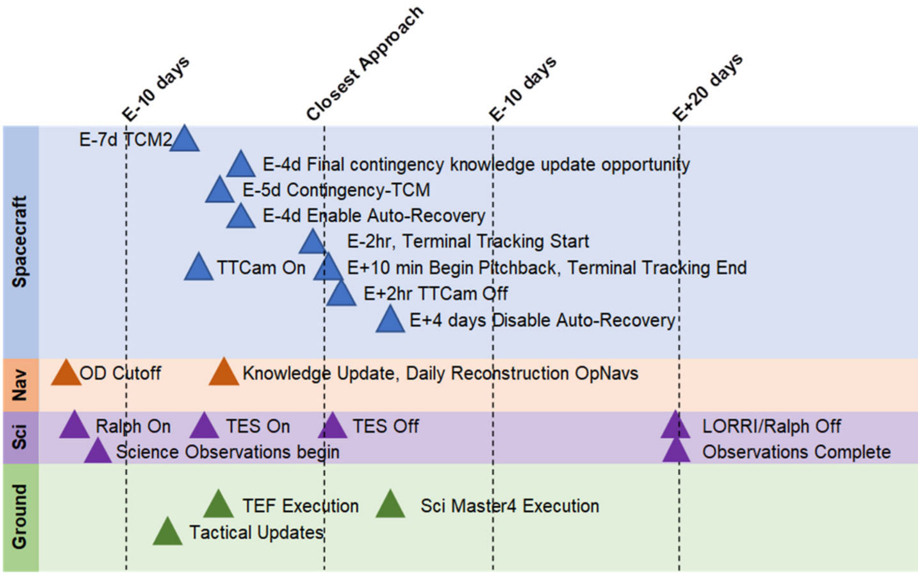

Fig. 8 Key activities during a Trojan asteroid flyby starting about 15 days before closest approach and continuing to 20 days after closest approach

the same instrument. For example, if a color scan with Ralph should execute given the current range estimate but the instrument is still completing a current observation, the pending color scan will be skipped. It is thus necessary to ensure that sequences can accommodate variations in the time-distance relationship and avoid collisions between consecutive instructions. This is ensured by scheduling sufficient time between subsequent observations/VML blocks of the same instrument.

2.1.2 Spacecraft Attitude During Encounters

The spacecraft and IPP attitude change over the course of the flyby to keep the instrument boresights pointed at the Trojan asteroids during the encounter. The concept of operations for the spacecraft and IPP attitude is dependent on the solar phase angle on approach. For encounters that approach from the sunward side of the Trojan asteroid where the solar phase angle is less than 90 degrees, Lucy is oriented in a "feet first" flyby which means that the spacecraft approaches the asteroid with the main engine ("feet") closer to the velocity vector than the IPP ("head"), see Olkin et al. (2021a). This is the encounter geometry for the Donaldjohanson, Eurybates, Polymele and PMB encounters. On approach, the high gain antenna (HGA) is pointed to the Earth with the spacecraft Y-axis orthogonal to the velocity vector. At E-2 hrs, the spacecraft attitude changes from pointing the HGA to Earth to aligning the spacecraft Z axis with the plane defined by two vectors:(1) the spacecraft to Trojan asteroid and (2) the Trojan relative velocity vector. To do this, the spacecraft rolls about the Z-axis. This rotation is small (less than 11°). The location of the Trojan asteroid is given by the on-board ephemeris at first. Once terminal tracking is enabled, the definition of this plane is determined by the state estimation from the terminal tracking. The time that state estimation is enabled is defined in the command load and will be based on simulations of the terminal tracking and state estimation performance based on the encounter geometry and best estimate shape models for the Trojan asteroid.

As the spacecraft approaches the Trojan asteroid, the spacecraft will rotate about the Y axis. This motion will take the solar arrays off the Sun and the HGA away from Earth. At E+10 minutes past closest approach, the spacecraft will perform a pitchback maneuver and rotate about the Y-axis to undo the rotation that took place during closest approach. This rotation will take about 35 minutes. During this time, the IPP will rotate to keep the Trojan in the instruments' FOVs and will return the spacecraft to a power positive state and communications with Earth through the HGA will be reinstated. For the Trojan encounters where the spacecraft is approaching from the unilluminated hemisphere (Dinkinesh, Leucus and Orus), the basic idea is the same except the spacecraft approaches with the IPP close to the velocity vector.

2.1.3 Science Planning and an Example Timeline

Science planning begins with the Level 1 science requirements (see Levison et al. 2021). To facilitate that planning, the science team has developed a series of short documents or "Measurement Techniques" that describe in detail attributes of the observations needed to accomplish the science objectives. An example illustrating the level of detail in the measurement technique is the range of illumination angles desired for observations designed to identify craters (discussed more in the next section). It is difficult to detect craters without shadows so the illumination angle of the observation is important. Measurement techniques are defined for the prime method for accomplishing the science as well as for backup observations including those that could be accomplished with an alternate instrument.

The Eurybates encounter will occur at a relative velocity of ~6 km/s and with a nominal close approach distance of 1000 km. Signal-to-noise considerations require observations to be done at a phase angle smaller than 82°. For the Eurybates encounter, the asymptotic phase angle is 81° on approach and 99° on departure. The phase angle will be 82° approximately 10 min after passage at closest approach. As such, most of the primary science observations will be done on the approach side for Eurybates.

Figure 9 shows a portion of the timeline of the encounter, with markings of where the instruments are being used. Instruments can be operated simultaneously, to the exception of MVIC and LEISA which are components of the RALPH instrument. Observations for the Level-1 science objectives begin around 12 days before closest approach (E-12 days), with L'LORRI observations designed to detect potential satellites and determine their orbits. The Satellite Orbit Determination Observations use a series of 19 image sets that start at E-11.8 days and ends at E-1 day. The goal is to sample the Szebehely sphere for a variety of orbital periods, and to get at least 3 data points per possible orbit. The cadence of the observations is adjusted as Lucy get closer to the target in order to adequately sample distant and close-in satellites.

Next, global coverage observations begin using L'LORRI, LEISA, and MVIC. These observations do not have a resolution requirement, but must be done at a cadence that ensures the entirety of the target's available sunlit surface is observed while aiming for the highest resolution possible. As Lucy approaches the Trojan asteroid, the phase angle varies little at long distances, and new portion of the target become visible solely through the asteroid's rotation. To ensure both complete coverage and redundancy, we perform 29 L'LORRI observations spaced by 1/27th of a rotation (0.325 hrs), as well as, 9 observations with MVIC and LEISA spaced by 1/7th of a rotation (1.25 hrs).

For some of the requirements that relate to observations of craters, there is an additional criterion that comes into play: the phase angle of the observation must be greater than 40° and smaller than 75°. This is further complicated by the uncertainty in the spacecraft's delivery, which change the time/range at which a particular phase angle configuration can be

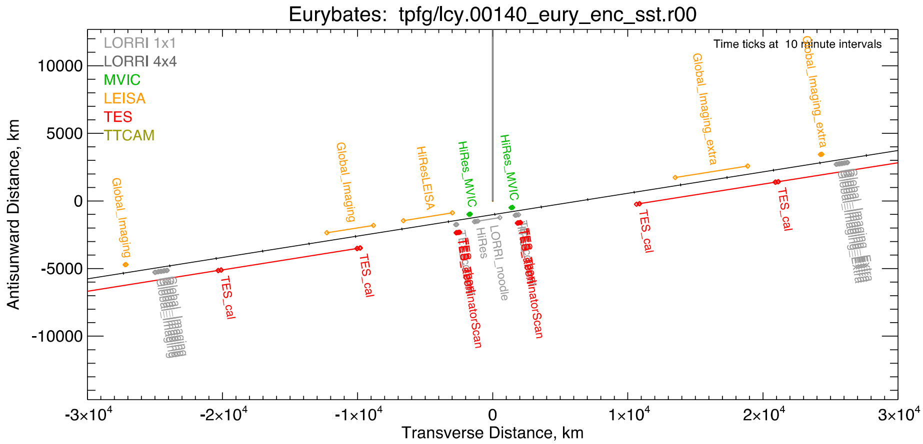

Fig. 9 A portion of the timeline of the Eurybates encounter

Table 4 Range and distance at which the desired phase angles occur for the 3σ low and high delivery at Eurybates. The first two columns are on approach and the last two columns are on departure

	75° phase angle	40° phase angle	40° phase angle	75° phase angle
3σ low case	8825 km at E-12m15s	1410 km at E-03m00s	1080 km at E+01m35s	2275 km at E+06m00s
3σ low	10258 km at E-29m25s	1639 km at E-03m39s	1255 km at E+01m50s	1644 km at E+07m00s

achieved. Table 4 shows the time and ranges at which the 40° and 75° phase angles happen for the 3σ low and high delivery (which correspond to a close approach distance of 925 km and 1075 km, respectively). The main consequence is that the opportunities to place observations that will give adequate data for all possible deliveries is reduced.

When planning science observations, we have adopted the stance to try and achieve our Level 1 Science Requirements with as few observations as possible. This leaves space for redundancy by giving more opportunities to place backup observations, and it also will allow us to implement additional observations to accomplish additional science. For example, an MVIC scan at 1900 km gives enough coverage and resolution to satisfy Level 1 Science Requirement 5 (panchromatic observation of 500 km^2 at 100 m resolution), 10 (color observation of 700 km^2 at 1500 m resolution) and 11 (color observation of 150 km^2 at 600 m resolution). These can be backed up by an additional MVIC scan at +1250 km. In general, we try to maximize the time between a Primary and Backup observation to build in resiliency.

Most of the other Panchromatic Level-1 Science Requirement are accomplished through the observations performed for global coverage, or via T2CAM imaging. The exception is the highest-resolution requirement of 10 km^2 at 29 m resolution (the latter is then expected to be improved to 14 m via deconvolution of successive L'LORRI exposures). This is implemented by a series of L'LORRI exposures (at a 1 second cadence) with very short exposure times, approximately 10 ms (to mitigates smear), as Lucy passes through closest approach.

For LEISA observations at Eurybates the combined areal coverage/resolution requirement is achieved by triggering a LEISA observation on approach at 6760 km. For time efficiency, this observation is divided into two separate scans. One covers the shorter wavelength with a shorter integration time and the other covers the long wavelength portion of the detector with a longer integration time. It takes about 10 min to complete the combination of these two scans. This observation ends just before we have to start moving the IPP to perform a terminator scan with L'TES (see next paragraph). Because of the lengthy duration of these scans, it is not possible to place a satisfactory backup on the departure side, as the scan could not be completed before the phase angle reaches 82 deg and the signal to noise degrades below the requirement. Instead, the last scan for global coverage at −12,500 km is a backup, leaving over 6.5 min between the prime and backup.

The L'TES instrument will take scans every 2 s starting 24 hours before closest approach (only interrupted by brief calibration operations approximately every 30 min). The only special pointing for L'TES will be to perform measurement of the target's unilluminated areas. This is implemented by having the IPP slowly drift across the target through the terminator. In order to measure the temperature of the Trojan asteroid's unilluminated surface at least 50% of the detector's FoV must be on the target without a view of the illuminated terrain. The relative sizes of the L'TES field of view and that of the target's unilluminated area is a combination of the phase angle (lower phase angle means larger portion of the target being illuminated) and Lucy's range to the target (closer range means the smaller the size of the TES FoV projected on the surface). At Eurybates, the configuration is such that the Primary and Backup terminator scans must be implemented on the approach and departure side, at 2290 km and 1575 km respectively.

A tool to simulate the encounters was developed to demonstrate that the area and resolution requirements of Lucy's Level 1 science objectives were met. This tool allows us to estimate the coverage and resolution we can expect to come out of a given science sequence. Figures 10 to 13 shows resolution maps for combined Panchromatic observation (L'LORRI, T2CAM and MVIC-Pan channel), MVIC-Color channels, LEISA, and L'TES. On each map,

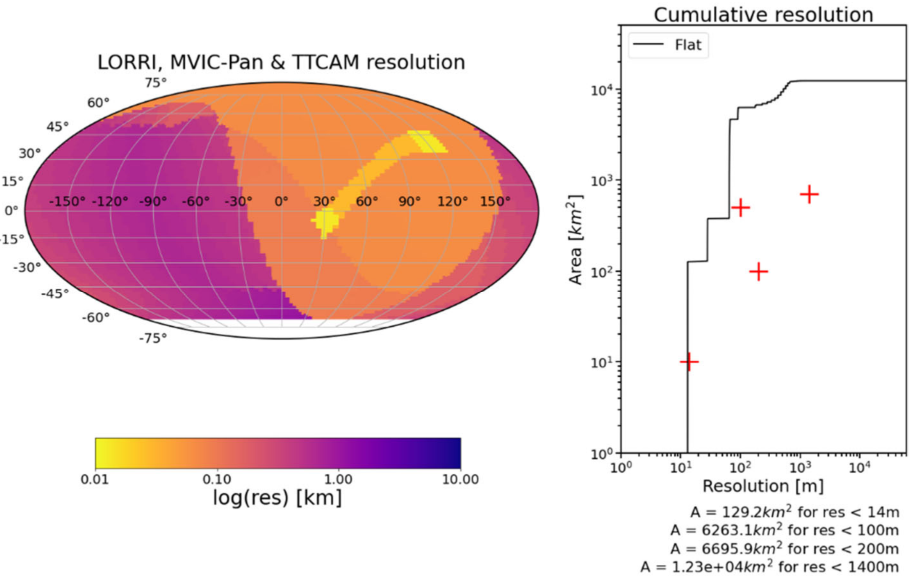

Fig. 10 Resolution map for all panchromatic observations using L'LORRI, T2CAM and MVIC-Pan. The map shows improved resolution where deconvolution of consecutive L'LORRI exposures is expected

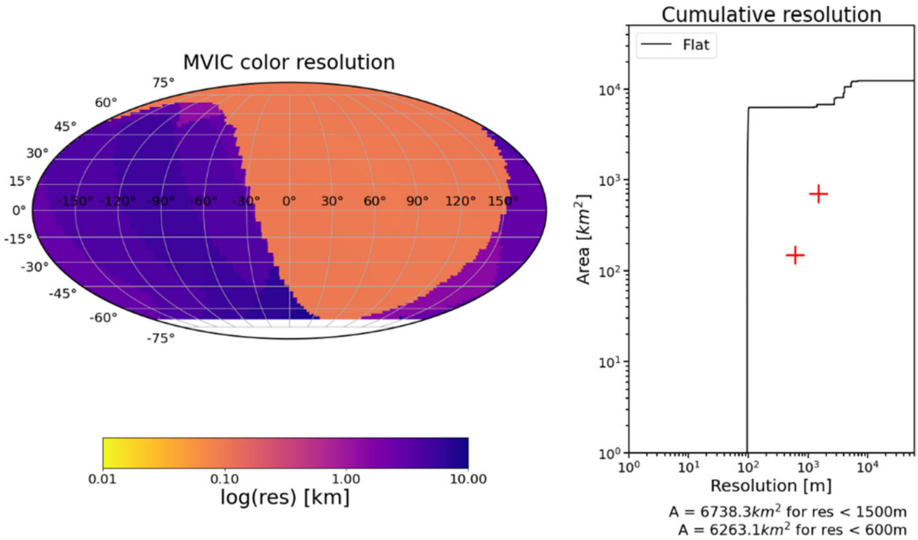

Fig. 11 Resolution map for all MVIC-Color observations

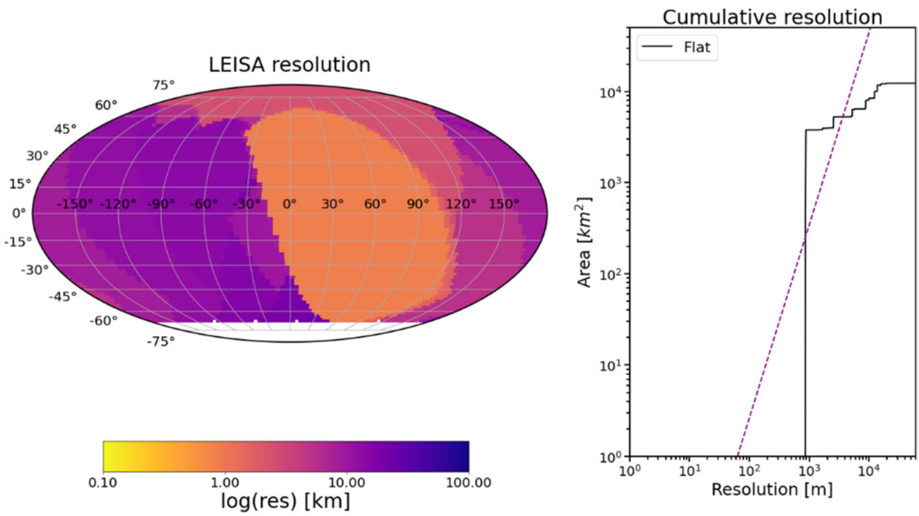

Fig. 12 Resolution map for all LEISA observations

the right side shows the cumulative resolution with science requirement of resolution/coverage showed as red crosses (for LEISA, the red dashed line shows the power-law that is the areal/resolution requirement for LEISA). The example sequence is estimated to give us sufficient coverage and adequate resolution to meet all Level 1 Science requirements.

Additionally, this tool can be used to perform a Monte-Carlo analysis of each science sequence. The Monte-Carlo analysis allows variation in Lucy's delivery to the encounter aim point, the on-board knowledge of the position of the target, and various properties of the target (shape, size). Using results of the state estimation convergence from the terminal

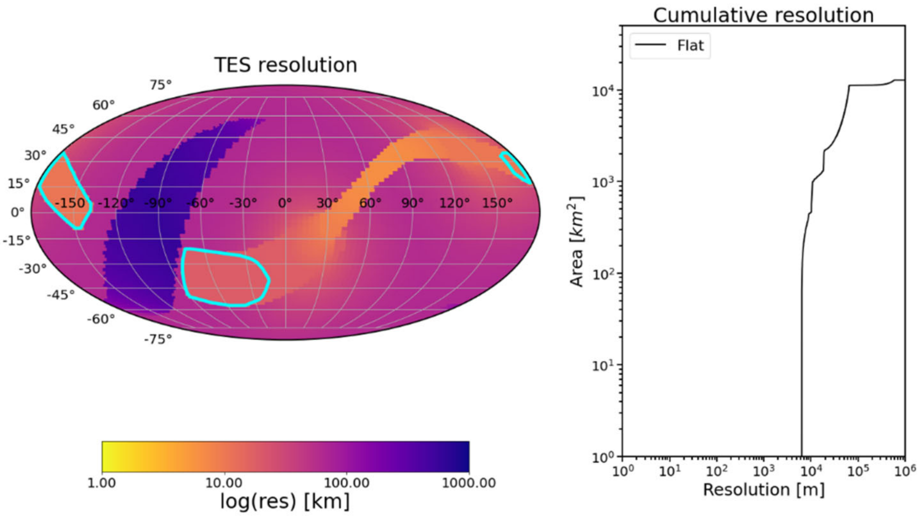

Fig. 13 Resolution map for all L'TES observations. The blue contour shows unilluminated areas observed

tracking, the Monte-Carlo analysis can investigate the resilience of a science sequence to the variation in the range estimates over time.

2.1.4 Resiliency in Encounter Planning

Spacecraft flybys are a time critical operation. If an opportunity is missed, it cannot be picked up at a later time. For this reason, the concept of operations includes a number if design elements that make the encounter resilient and time efficient. When the science timeline for observations is constructed, the highest priority observations are the ones that accomplish the Level 1 science objectives (Olkin et al. 2021b). The next priority is backup observations for the Threshold science objectives. The back up observations are preferably placed more than 5 minutes from the prime observations for an objective. This time spacing is important because in at least some failure modes, the fault protection system can recover to join the science sequence in about 5 minutes.

In addition to backup observations, we consider additional observations that can address the objective with another instrument if possible. This provides an ability to address an objective, perhaps in a degraded manner, if one of the instruments has a problem during the encounter. The L'LORRI and L'Ralph-MVIC instruments can provide backups for each other, however, with the different resolutions and fields of view of the instruments, the backup observations with an alternate instrument may be degraded.

The Lucy mission has incorporated tactical updates, to mitigate Trojan surprises, that modify select instrument activities no later than E-4 days, without modifying the command sequence files, sequences or block libraries or overall block/sequence execution timing. These updates will be designed in a manner that does not require the Flight Team to re-build tested and verified sequences (i.e., the update cannot change sequences or block timing). The intent is to prevent activity duration increase that could lead to adjacent activity overlap and conflicts. But it does not preclude activity duration reduction. For L'LORRI, the tactical update is exposure level adjustment to go up or down with a maximum adjustment factor of 2 via a global variable. For instance, a 100 ms exposure observation could be updated to either 50 ms or 200 ms. For Ralph MVIC, the tactical update is a TDI row adjustment, a default readout of 32 TDI rows could be changed to 16 or 64 depending on target brightness but would not change the scan rate of the Ralph mirror and the corresponding observation duration.

3 Conclusions

The flyby mission architecture allows 8 Trojan asteroids to be visited by one spacecraft. This is important for the first exploration of the Trojan asteroids and allows Lucy to observe the diversity of the Trojan asteroids (Levison et al. 2021). The use of a trajectory with a periapse near Earth and an apoapse near the Trojan swarms provided an opportunity to visit both the L4 and L5 Trojan swarms. Additionally, the mission design allowed for a rehearsal of the flyby with the main belt asteroids Dinkinesh and Donaldjohanson which reduces risk for the Trojan encounters.

The concept of operations was streamlined across Trojan encounters as much as feasible to help the operation team and to reduce risk by having a repeatable pattern of activities. The mission team's goal was to provide a platform that would allow flexibility in observation planning in the future. This was accomplished by having the system allow for observations by any instrument with only minimal restricted times. To be efficient during the flyby, Lucy includes a terminal tracking system that estimates the location of the Trojan target. This collapses the relatively large (in angular terms) uncertainty ellipse that would need to be covered without the terminal tracking capability.

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Declarations

Competing Interests The authors declare no competing interests.

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