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TERMINAL TRACKING FOR THE LUCY TROJAN ASTEROID MISSION

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The most recent NASA Discovery class mission to fly is the Lucy mission to the Trojan Asteroids of Jupiter. Launched in October of 2021, Lucy's destination will be the unexplored Jupiter Trojan Asteroids that orbit the Sun at the stable L4 and L5 points ahead of, and behind Jupiter. This 12-year mission will perform close flybys of 1 main belt asteroid, Donaldjohanson, and 7 Trojans asteroids: Eurybates and its satellite Queta, Polymele, Leucus, Orus, and the near equal mass Trojan binary pair, Patroclus and Menoetius. The large distance from earth for the encounters, the high relative velocities and sun incidence angles on approach, and the limited number of Earth observations of the Trojans, make the delivery knowledge highly uncertain. To reduce the delivery uncertainties and maximize science return, Lucy employs a Terminal Tracking System consisting of optical imaging, centroiding and state estimation of the Trojan asteroids on approach and through close approach. This paper presents the Lucy Terminal Tracking System implementation, a brief overview of the mission and the GN&C subsystem.

INTRODUCTION

In this paper, we begin by briefly discussing the Mission overview, including the unique navigation path to flyby 7 Trojan asteroids in 12 years. There is a brief discussion of the mission science objectives and the science instruments, including how the science requirements drove unique aspects of the Lucy spacecraft design. This is followed by an overview of the Lucy Spacecraft and the Guidance, Navigation and Control (GN&C) Subsystem in particular, including the GN&C hardware components. The Encounter Phases of the mission are discussed, showing the commonality of the mission concept of operations (ConOps) timeline as well as the unique aspects of each encounter. Finally, the Terminal Tracking System, which acquires and helps the spacecraft track the targets during the science critical few hours around close approach is presented.

MISSION OVERVIEW

NASA's Lucy mission is a Discovery Class mission which will explore seven Trojan asteroids at the L4 and L5 Lagrange points of Jupiter as well as one main belt asteroid. The Lucy mission is named after the fossilized skeleton of an early hominid found in Ethiopia on Nov 24, 1974, by Donald Johanson and Tom Gray. As the Lucy fossil provided insights into humanity's evolution, the Lucy mission will add to scientists' knowledge of planetary origins and the formation of the Solar System. The trajectory and timeline of the mission is shown in Figure 1. Lucy successfully launched on October 16, 2021 and is in the process of performing initial spacecraft and instrument checkouts and calibrations. Lucy will perform two Earth Gravity assist flybys in 2022 and 2024 before heading out to its asteroid encounters. The first of these encounters will be a demonstration flyby of the main belt asteroid Donaldjohanson, named after one of the discoverers of the Lucy fossil. The first set of Trojan asteroid encounters will occur from August 2027 through September 2028 when it will fly by four of the L4 Trojans: Eurybates and its satellite Queta,

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Polymele, Leucus and Orus. After another Earth gravity assist in 2030 the spacecraft will pass through the trailing L5 swarm of Trojans asteroids and encounter the near equal mass Trojan binary pair Patroclus and Menoetius in 2033. The flyby of this binary asteroid pair and the subsequent return of the science data will complete the planned mission for Lucy.

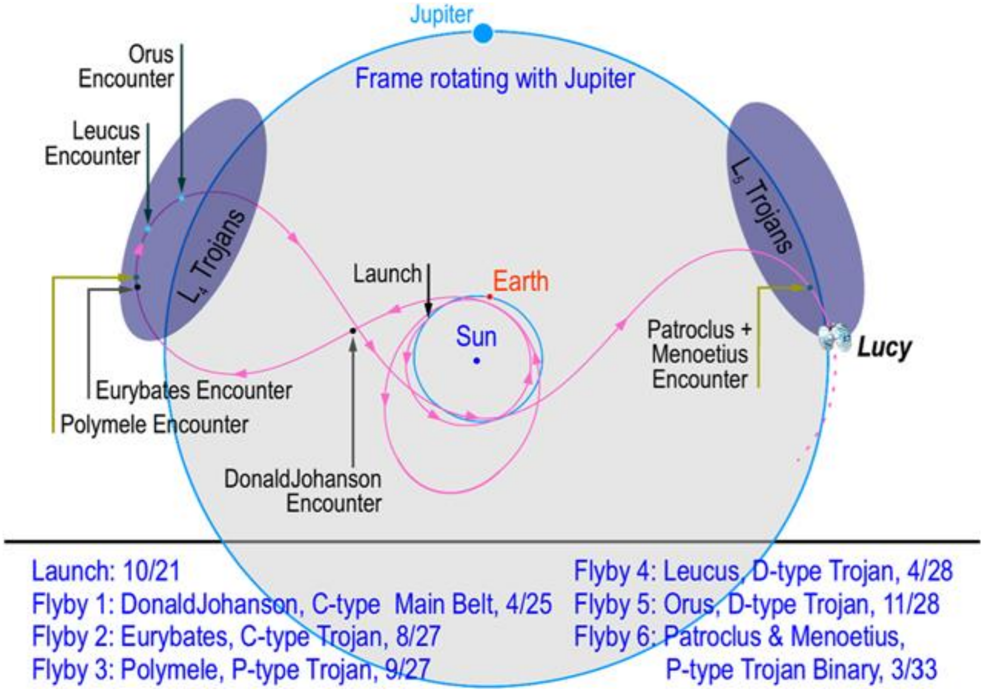

Figure 1. The Lucy trajectory is shown in a frame rotating with Jupiter. [1]

INSTRUMENT AND SCIENCE OVERVIEW

The Science Payload on Lucy is comprised of three instruments, a dual use camera system and the dual use telecom system. The Lucy Long Range Reconnaissance Imager, L'LORRI, is a high-resolution panchromatic camera with a 0.29-degree FOV and 5 μrad/pixel iFOV. L'Ralph is a color imager and short-wavelength infrared imaging spectrometer with two different focal planes: the Multispectral Visible Imaging Camera (MVIC) with an 8.3-degree FOV and 29 μrad/pixel iFOV; and the Linear Etalon Imaging Spectral Array (LEISA), which has a 1.4x3.4-degree FOV and 80 μrad/pixel iFOV. The Lucy Thermal Emission Spectrometer (L'TES) is a thermal infrared spectrometer with a 0.57-degree FOV. The L' on the instrument names is to distinguish their Lucy versions from predecessors on other missions. The Terminal Tracking Camera (TTCam) has a dual use as the imaging camera for the Terminal Tracking System during encounter, and as a science instrument for shape modeling purposes. An additional dual-use component is the spacecraft High Gain Antenna telecommunication system, which performs the mission Radio Science (RS), measuring the Doppler shift during the flybys. The layout of the instruments on the IPP are shown in Figure 2.

As can be seen in Table 1, which shows the mapping of the mission baseline science requirements to the various science instruments, many of the science requirements are to obtain surface imaging at specific resolutions. These surface resolution requirements were a driver in the range based pointing requirements and the implementation of range-based sequencing in the spacecraft design. These will be discussed in more detail in the Terminal Tracking System discussion.

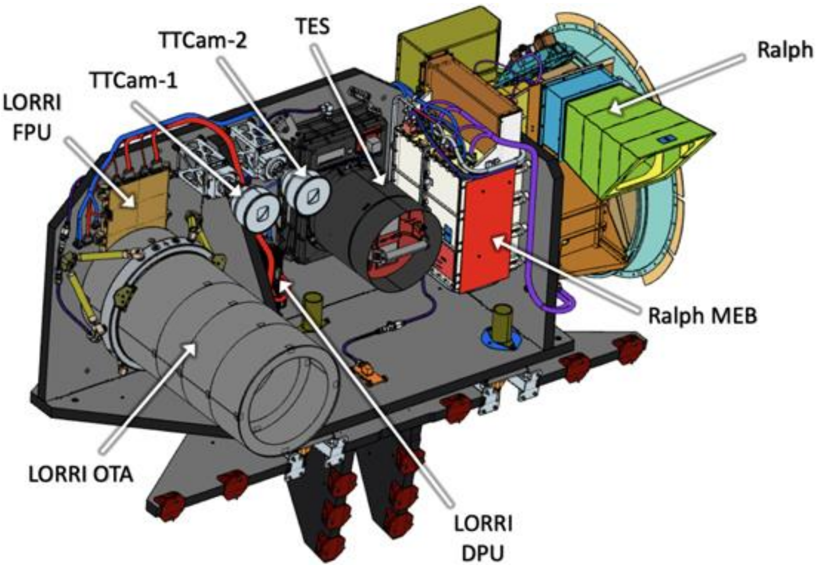

Figure 2. The Instrument Pointing Platform (IPP). From left to right, the instruments are: L'LORRI, two Terminal Tracking Cameras (TTCam-1 and TTCam-2), L'TES, and L'Ralph. [1]

Table 1. Mapping from baseline mission science requirements to the science instruments. The instruments abbreviations are L'LORRI (LOR), MVIC (MVI), the Terminal Tracking Cameras (T2C), LEISA (LEI), L'TES (TES), and Radio Science (RS). The fully filled circles indicate instruments that can completely accomplish the requirement. The half-filled circles indicate the instrument partially contributes to the requirement. The quarter-filled circle indicates that this instrument provides a degraded backup for the requirement. Finally, an open circle indicates that the instrument does not contribute to the requirement. [1]

No	Descriptor	Baseline Requirement	LOR	MVI	T2C	LEI	TES	RS
1	Targets	Patroclus,Meneotius, Eurybates, Leucus, Polymele, and Orus	○	○	○	○	○	○
2	Shape and Geology	Pan images: full rotation spaced by 1/25 to 1/13 of a rotation	◑	◑	●	○	○	○
3	Shape and Geology	Pan images: series of phase angles separated by 15°- 25°	◑	◑	●	○	○	○
4	Elevation Models	Pan images: area ≥ 100 km^2; resolution ≤ 200 m, two stereo emission angles	●	◑	●	○	○	○
5	Landform Degr.	Pan images: area ≥ 500 km^2; equator to 60°lat.; resolution ≤ 100 m	●	●	●	○	○	○
6	Craters	Pan images: area ≥ 700 km^2; resolve craters d > 7 km	◑	●	●	○	○	○
7	Craters	Pan images: area ≥ 10 km^2; resolve craters d > 70 m	●	◔	◔	○	○	○
8	Satellite Search	Search: satellites d ≥ 2 km, $p_v > 0.04$ within $R_{Szebehely}$	●	◑	○	○	○	○
9	Global Color	Color images: full rotation spaced by 1/6 to 1/3 of a rotation	○	●	○	○	○	○
10	Low-Res Color	Color images: area ≥ 700 km^2; resolution ≤ 1.5 km	○	●	○	○	○	○
11	High-Res Color	Color images: area ≥ 150 km^2; resolution ≤ 600 m	○	●	○	○	○	○
12	NIR Range	Spec: spectral range 1.0-3.8 μm	○	○	○	●	○	○
13	NIR Perf.	Spec: detect features with spectral depth $\geq 4\%$ and width of ≥ 70 nm	○	○	○	●	○	○
14	Compositional Variation	Spec: full rotation spaced by 1/6 to 1/3 of a rotation	○	○	○	●	○	○
15	Composition	Spec: resolution (r) and areal coverage (A) satisfy $r \leq 2(A/1470.6)^{0.473}$ km	○	○	○	●	○	○
16	Mass	Targets: mass accuracy $\leq 25\%$, for $\rho \geq 1000$ kg/m^3	○	○	○	○	○	●
17	Thermal	Thermal: 1 unilluminated surface; 3 sunlit with 1 at $< 30°$from subsolar point	○	○	○	○	●	○

SPACECRAFT OVERVIEW

The Lucy Spacecraft will be powered by two 7.2m solar arrays which generate 504 watts at the furthest encounter distance, making it the furthest from the sun solar powered spacecraft when it reaches 5.8 A.U., eclipsing the JUNO spacecraft's record. The spacecraft has dimensions of 14.25 meters wide by 7.2 meters high by 3.8 meters deep when the solar panels have been deployed. It has a dry mass of 821 kg and a wet mass fully fueled of 1550 kg. Lucy has a dual mode propulsion system made up of Hydrazine monopropellant and Hydrazine/Nitrogen Tetroxide bipropellant capability. The mono-prop system is used for Trajectory Correction Maneuvers and Attitude Control (3 axis pointing, slews, and reaction wheel desaturation) and consists of eight 0.9 N ACS thrusters and six 22 N TCM thrusters. The bi-prop system is used for large delta-V maneuvers and consists of a single 460 N Leros 1C engine. The propellant is stored in three tanks (2 fuel and one oxidizer). Telecom is accomplished through a 2m High Gain Antenna (HGA) for high-rate communications far from earth, a Medium Gain Antenna (MGA) for near-earth communication periods, and a wide field of view Low Gain Antenna (LGA) for low rate and anomaly communications.

GUIDANCE, NAVIGATION AND CONTROL (GN&C) SUBSYSTEM DESCRIPTION

The GN&C component locations on the spacecraft are shown in Figure 3. The components consist of two Honeywell Miniature Inertial Measurement Units (MIMU), a HYDRA Baseline LEO Star Tracker Assembly (2 Optical Heads and 2 Electronics Units), four Honeywell Constellation Series HR16-25 Reaction Wheel Assemblies (RWA), and two Adcole analog 4-head Sun Sensor Assemblies (SSA).

For attitude determination (AD) the Star Trackers provide attitude quaternion estimates at 10 Hz while the MIMUs utilize three orthogonal ring laser gyros to provide angular rate data at 200 Hz. Attitude estimation is performed by a 6-state extended Kalman filter [8] which combines attitude quaternion measurements from the star tracker with angular rate measurements from the MIMU to produce 3-state attitude error estimate and gyro bias estimate.

For Attitude Control (AC) Lucy uses a variety of actuator components. Nominal 3-axis control employs three orthogonal reaction wheels aligned about the Y axis of the spacecraft, which provides maximum torque and momentum capability about the Y axis, which is the main axis of rotation for Encounters. A fourth, cold spare skew wheel is aligned with the Y axis of the spacecraft, allowing it to be used for three axis control in case of failure of one of the main wheels. Each reaction wheel has 0.25 N-m of torque capability and 25 N-m-s of momentum capacity, allowing the spacecraft to pitch over and track the Trojans at rates up to 1 degree per second during encounters. For attitude control during spacecraft emergencies, delta-V maneuvers and RWA momentum desaturations, the eight coupled ACS thrusters are used.

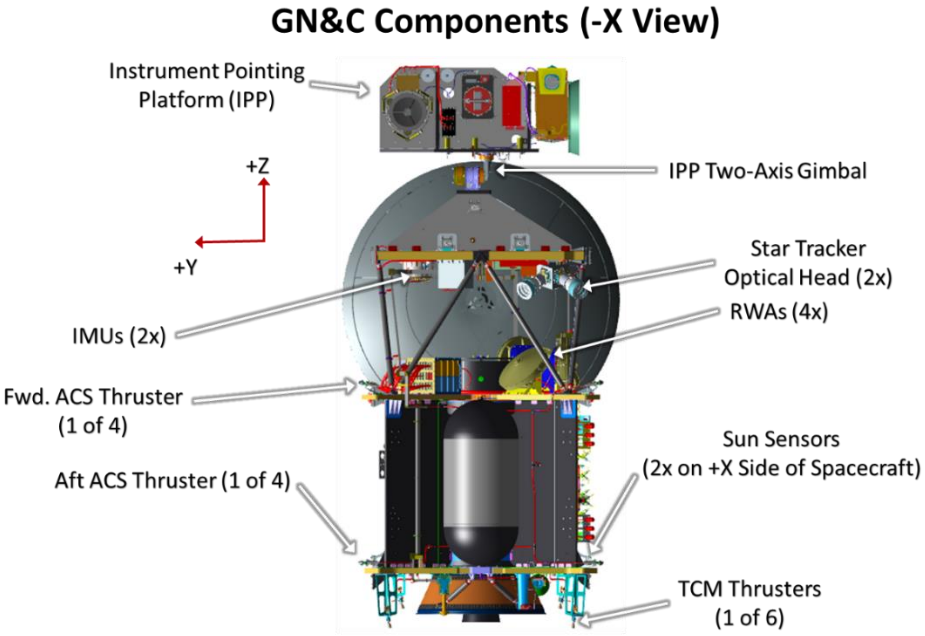

Figure 3. Simulated view of the spacecraft with GNC component placement.

The Lucy GN&C is also responsible for the pointing of the Instrument Pointing Platform (IPP), which houses the science instruments and the Terminal Tracking Cameras (TTCam). The IPP is articulated through a two-axis gimbal which is driven by a dual winding brushless DC harmonic drive motors with redundant 20-bit resolvers and which have a maximum speed of 2 deg/sec per axis. The articulated IPP provides high accuracy pointing and stability for the instruments, critical for approach OpNav imaging and high stability pointing for science during Encounter Close Approach. The Malin Space Science Systems redundant TTCam have the primary purpose of imaging the targets during close approach as part of the Terminal Tracking System to update onboard knowledge of the target location relative to the spacecraft. They have a wide 10.8 degree by 8.1-degree field of view to enable them to image the entirety of largest of the Trojans at their closest approach. The TTCam pixel resolution of 74 micro-radians is fine enough to allow it to resolve the smallest of the Trojans within the final hour of its closest approach. The images taken by the TTCam will also serve the dual purpose of providing shape modeling information for the mission science objectives.

ENCOUNTER

The Encounter Phase for each of the flybys follows the same timeline, as shown in Figure 4. The Acquisition period begins at E-60 days and involves acquiring the target with the LORRI instrument through long duration exposures. The Approach period involves putting the spacecraft on the proper trajectory for Encounter through Trajectory Correction Maneuvers. The Close Approach period from E-4 to E+4 days is the primary science collection period, and the spacecraft operates autonomously with no commanding from the ground. During the Depart period, the spacecraft performs the data playback from the encounter. In order to maximize reuse of flight products and simplify operations, all five Encounters follow the same timeline, with the Eurybates and Polymele Encounter timelines overlapping due to the 30-day separation between their close approach dates.

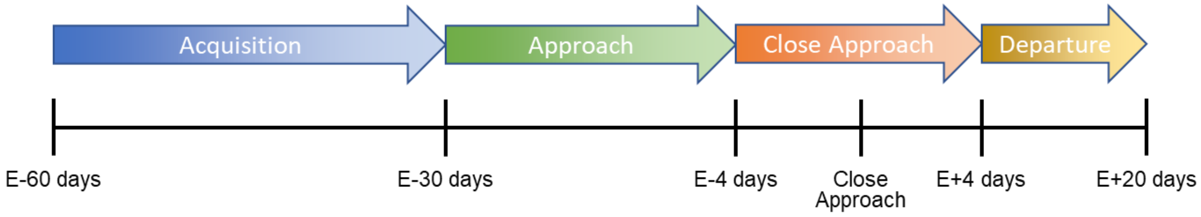

Figure 4: Lucy timeline is identical for all Encounters.

Table 2: Unique aspects for each of the Trojan Encounters.

Body	Approach Solar Phase Angle (deg)	Encounter Velocity (km/s)	Radial Distance Aimpoint (km)	3-Sigma Large Projected Axes Size (Long/Short, km)
Eurybates	81	5.7	1000	106 x 97
Polymele	82	6	434	50 x 37
Leucus	104	5.9	1000	63 x 30
Orus	126	7.1	1000	95 x 84
Patroclus/Menoetius	56	8.8	1245 (P) 1075 (M)	132 x 122 (P) 122 x 113 (M)

While the timeline for each encounter will follow the same pattern, each encounter has its own unique aspects and challenges, as shown in Table 2, which summarizes key aspects for each encounter. The encounter velocity varies from 5.7 to 8.8 km/s; the approach phase angle varies from a minimum of 56 to

126 degrees; the radial flyby distance, key to obtaining gravity science, varies from 434 km to 1245 km; and the predicted size varies from 50x37 km to 132x122 km.

On approach to the targets at E-60 days the spacecraft remains in an Earth/Target attitude, with the HGA pointed at Earth for communications and the plus or minus Z axis of the spacecraft in the Earth/Spacecraft/Target plane, and the IPP tracking the target, see Figure 5. At E-2 hours, the spacecraft transitions to Target/Velocity tracking, with the spacecraft pitching over about its Y axis to track the target while maintaining its plus or minus Z axis in the plane defined by the Target/Spacecraft/Velocity. During this period the IPP is compensating for spacecraft pointing and stability errors while also performing off-pointing, scans and retargets as needed to achieve the desired science. At E+10 minutes, the spacecraft pitches back about its Y axis to a power positive Earth/Target attitude while the IPP unfolds in the opposite direction, maintain pointing on the target and continuing to acquire science. Representative spacecraft rate profiles and IPP angles can be seen in Figure 6 for the Polymele flyby and Figure 7 for the Patroclus/Menoetius binary Encounter.

TERMINAL TRACKING SYSTEM

Due to the large distances from Earth that the Trojan Encounters occur, the on-board knowledge of where the Trojans are relative to the spacecraft will not be well known as the spacecraft approaches during the final hours. Even using the LORRI instrument in the months leading up to the Encounters for optical navigation (OpNav) imaging to improve the location knowledge, there can still leave hundreds of kilometers of location uncertainty during the encounter, as seen in Figure 8. With the Trojans being as small as 15 km to as large as 132 km in size, this uncertainty could cause the science instruments to completely miss the target at the ideal opportunity to image and collect data. For this reason, Lucy employs a Terminal Tracking System (TTS) to autonomously image the Trojan targets in the final hours of approach and to update the onboard knowledge of the target locations without intervention from ground operators. The centroiding and state estimation portions of TTS are like what has been used on other flyby missions such as Stardust [2] and described in [6]. TTS is comprised of a Terminal Tracking Camera (TTCam) to image the Trojans in the final hours and minutes of close approach, as well as on board centroiding, state estimation and target reference software to update the encounter flyby states and location of the targets, see Figure 9. The redundant TTCams have a wide 10.8 degree by 8.1-degree field of view to enable them to image the entirety of largest of the Trojans at their closest approach, while the TTCam pixel resolution of 74 micro-radians is fine enough to allow it to resolve the smallest of the Trojans within the final hour of its closest approach.

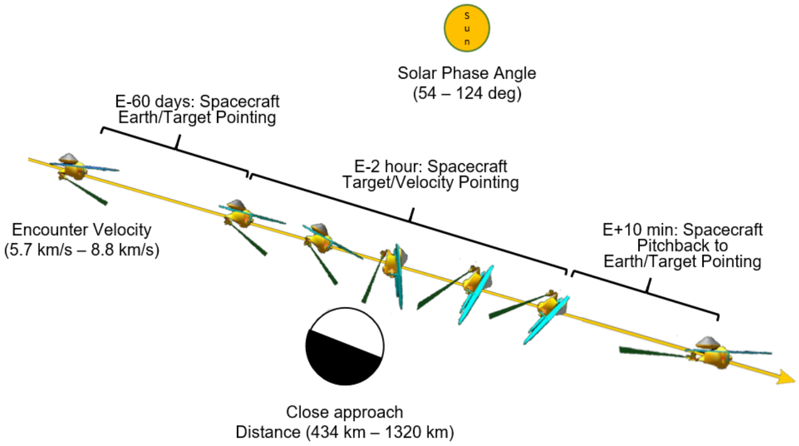

Figure 5: Tracking during Encounter transitions from fixed Earth Pointed while tracking with the IPP, to combination spacecraft and IPP tracking, and returning to fixed spacecraft with tracking IPP on departure.

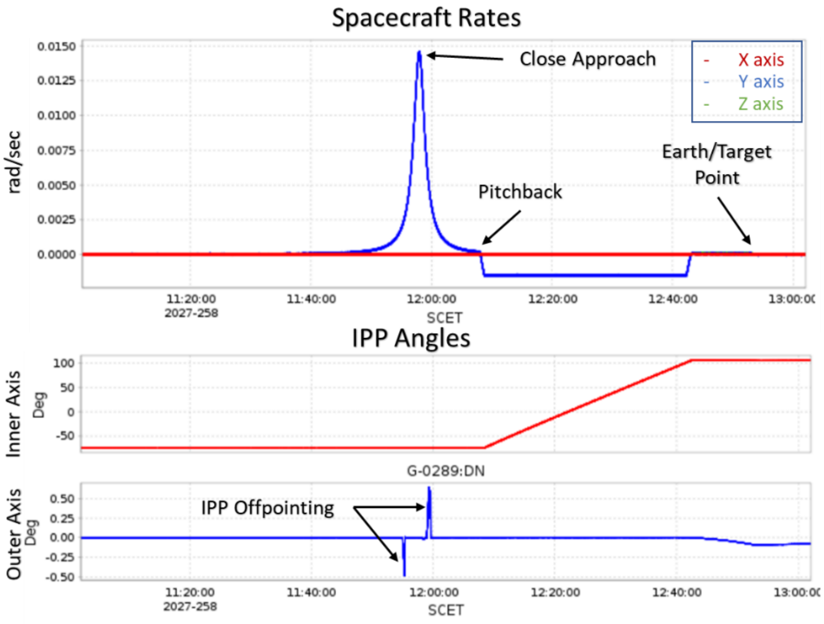

Figure 6: Spacecraft rate profile and IPP angles for the Polymele Encounter show max rate near close approach and IPP Off-pointing capabilities.

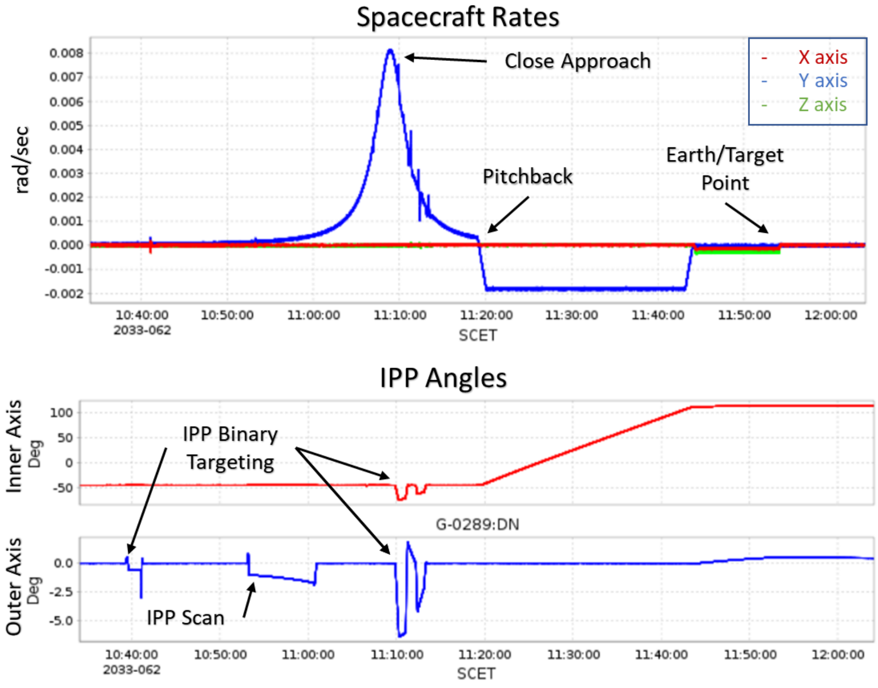

Figure 7: Spacecraft rate profile and IPP angles for Patroclus/Menoetius binary Encounter show the IPP retargeting capability between the two targets while the spacecraft maintains pitch-over tracking.

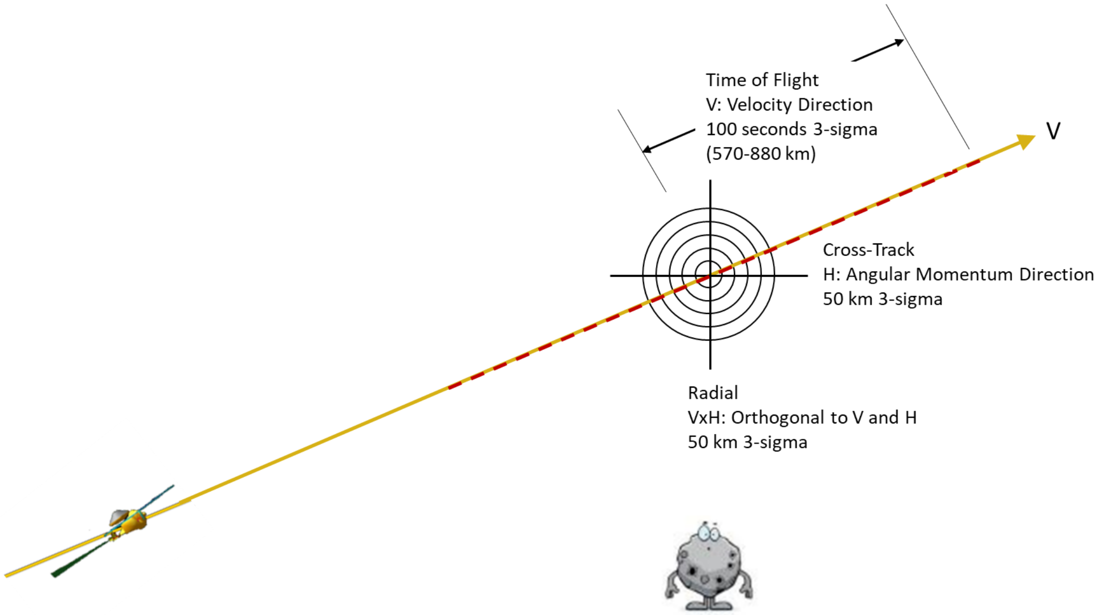

Figure 8: Knowledge of the spacecraft final delivery relative to the target can vary by as much as 50 km (3-sigma) in the Radial and Cross-Track direction and 100 seconds in Time of Flight.

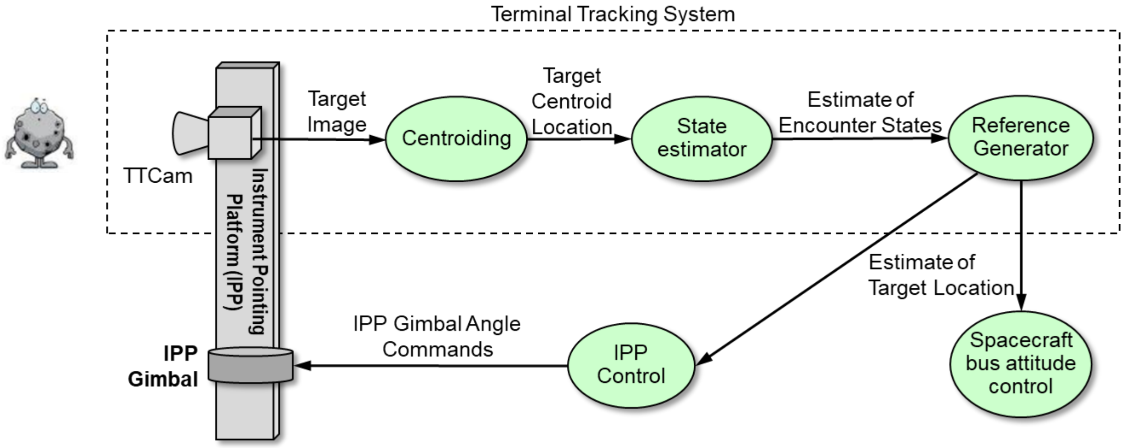

Figure 9: Terminal Tracking System accommodates Nav uncertainties for instrument pointing through autonomous, onboard imaging and updating of the target flyby states and location.

Centroiding

The Centroiding portion of TTS uses a method like that employed on Stardust [2] in combination with algorithmic methods presented in [3,4,5]. TTCam images are passed to the centroiding software, along with spacecraft estimate of the TTCam inertial pointing at the time of the image. The image is converted to a binary based on configurable thresholds, then sorted into connected components, which are merged, based on configurable proximity, into identified blobs. These blobs are given an inertial direction and time and passed to the State Estimator. This process is summarized in Figure 10. Additionally, because of the changing sun phase angle during the approaches, a phase angle correction is applied to convert from the identified blobs to an estimated center of target. This is based on a spherical shape model with a parameter that sets the strength of the correction. The strength of the correction is adjusted along with the threshold used by centroiding when converting to a binary to produce the desired amount of correction. Figure 11 shows an example of how the phase angle correction estimates the center of the target from a high sun phase angle image.

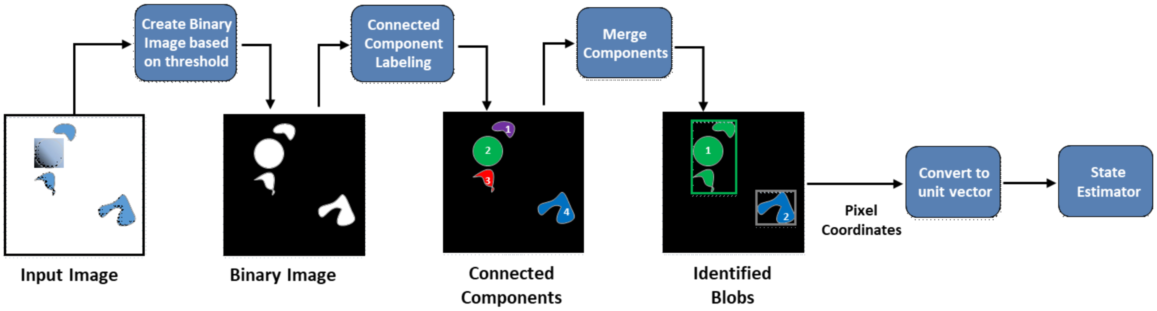

Figure 10: This diagram represents the logical steps required to identify blobs from a TTCam image and convert to an estimate of the target's inertial location for use in State Estimation.

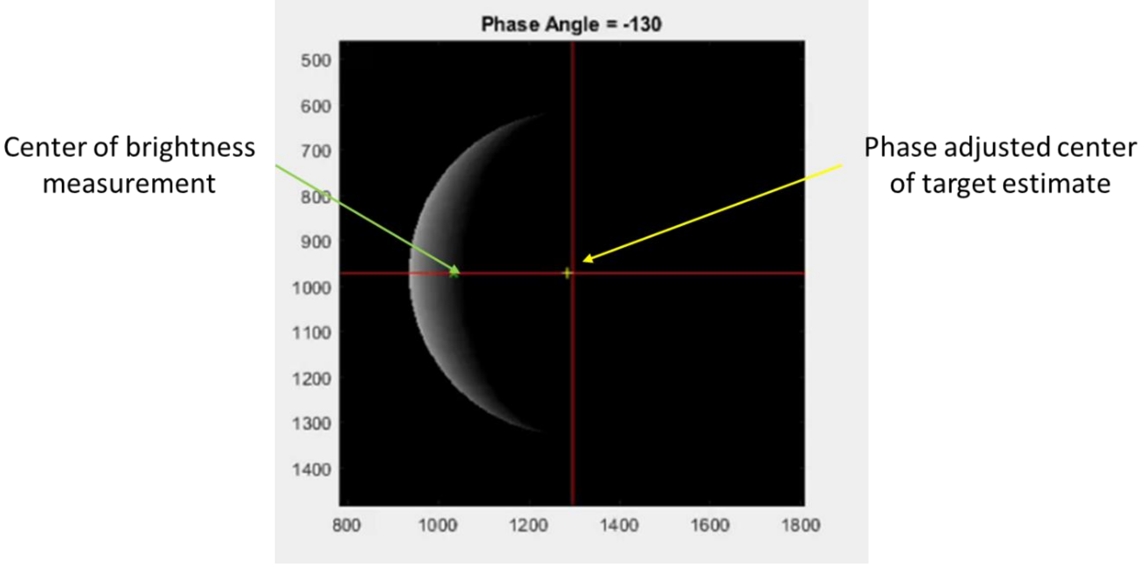

Figure 11: Centroid location adjustment based on phase angle and sun vector direction projected into the image.

During the analysis phase of the Lucy mission, tens of thousands of flybys were simulated and hundreds of thousands of images were rendered to verify the performance of the TTS. During this detailed analysis, it was discovered that the initial design, which estimated the center of mass of the target for use in instrument pointing, did not meet science collection requirements at some of the high phase angle approaches, when the lit portion of the target could be some distance away from the physical center of the target. The center of brightness measurement of the target was added to the centroiding identification and a propagated estimate of the center of brightness was added to TTS as an option for the IPP pointing during high sun incidence targets. A representative centroiding result using a rendered image, with center of mass and center of brightness estimates, is shown in Figure 12 and demonstrates the advantage of these two pointing options.

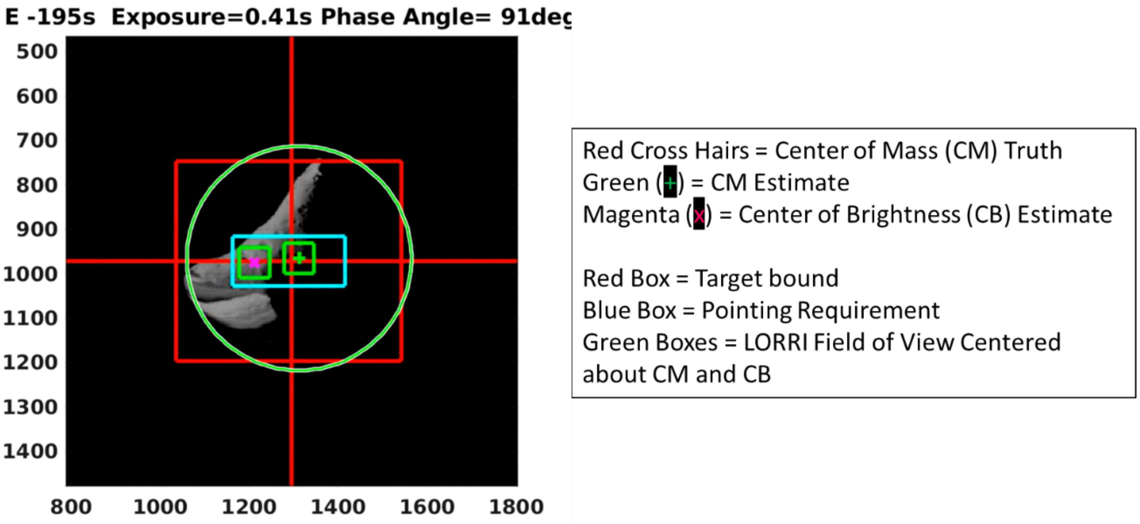

Figure 12: Representative centroiding result for a 91-degree Sun incidence angle image at close approach minus 195 seconds. LORRI field of view boxes in green show value of center of brightness pointing vs center of mass pointing at this time for a LORRI image.

State Estimator

The TTS employs a standard Extended Kalman Filter (EKF) [6, 8] to determine the position of the center-of-mass of the object being tracked in the inertial (Encounter) frame. This position is output as a delta position correction vector of the asteroid's position relative to the spacecraft at close approach, see Figure 13. The Target Reference Generator uses the correction vector estimate to provide more accurate pointing targets for the spacecraft and IPP as seen in Figure 14.

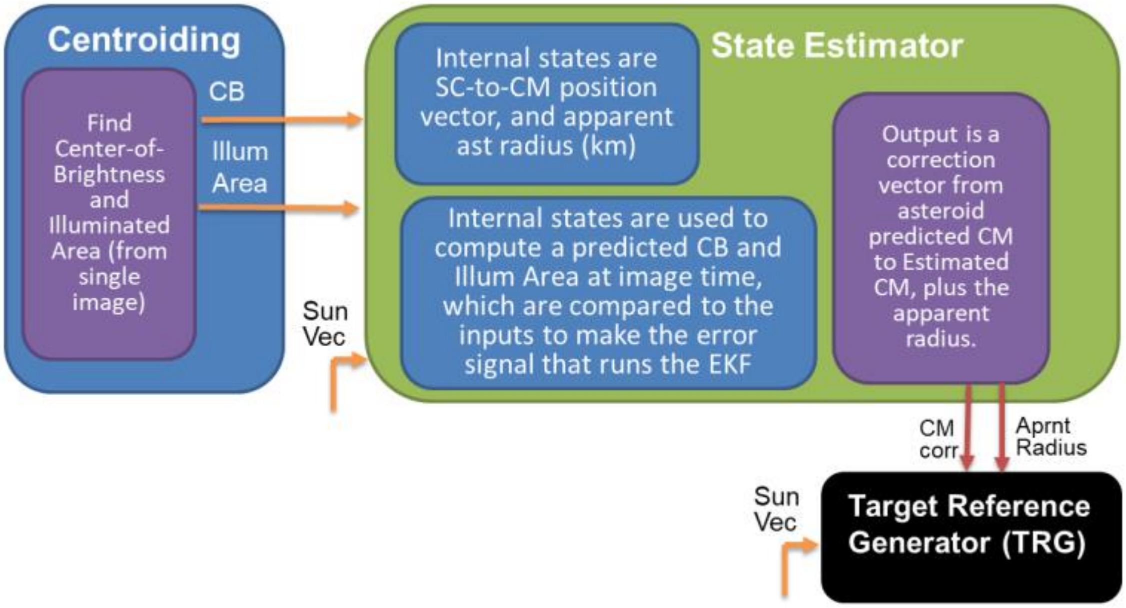

Figure 13: High level block diagram showing State Estimator functioning in Terminal Tracking in combination with Centroiding and Target Reference Generation.

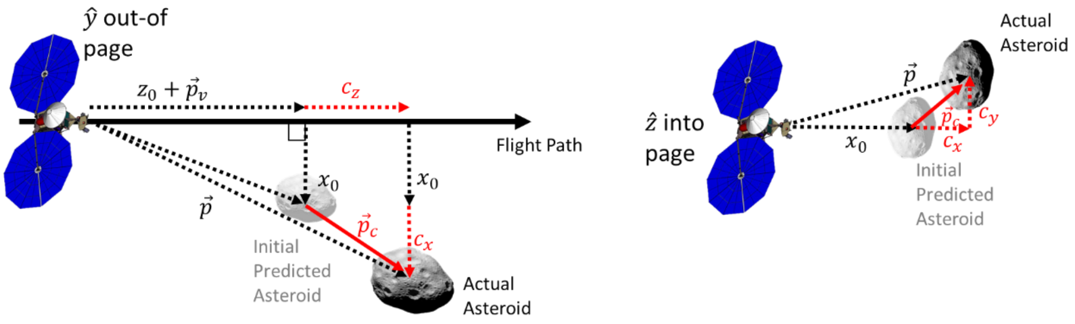

Figure 14: Encounter Frame Geometry. $\vec{p} = [x, y, z] = \vec{p}_0 + \vec{p}_v + \vec{p}_c$, the internal state vector, is the relative position vector from SC to estimated actual asteroid. $\vec{p}_c = [c_x, c_y, c_z]$ is the position correction vector from the initial predicted location of the asteroid to the estimated position.

The main part of the EKF state vector is the spacecraft to asteroid position vector, $[x, y, z]$, at the time of the latest measurement. The apparent radius of the asteroid, r, is used to convert between center-of-mass (CM) and center-of-brightness (CB) propagation. In addition, two bias states, α and β, are included to estimate camera-frame misalignments. This makes the EKF state vector:

$$\bar{x} = [x, y, z, r, \alpha, \beta]^{\mathrm{T}} \qquad (1)$$

A sample simulation result for the TTS Centroiding and State Estimation performance is shown in Figure 15 for a Eurybates flyby. As mentioned in the Instrument and Science Overview discussion, the pointing requirements are range-based, driven by the surface resolution baseline requirements and the smallest FOV science instrument, LORRI at 0.29-degrees. The spacecraft pointing must point to within ½ of the LORRI FOV when the target is less than twice the angular size of the FOV, otherwise, when the target is greater than twice the angular size, the spacecraft must point to within ¼ the angular size in the along-track direction and 1/8 the size in the cross-track direction. The along-track direction is in the encounter plane defined by the spacecraft velocity vector and the spacecraft to target vector. The cross-track direction is defined as normal to that plane.

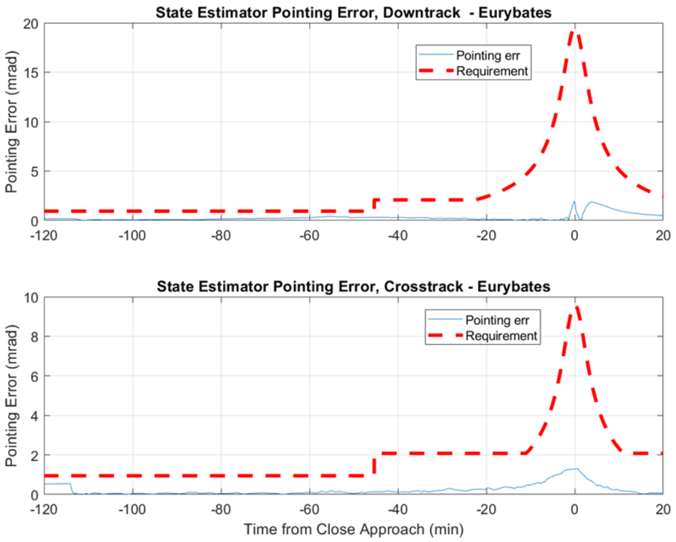

Figure 15: State estimator performance for a simulated Eurybates flyby compared to range and target size-based requirements.

A separate state estimator was implemented for the binary encounter to estimate the orbital states of the binary system. This employs the Advanced Nonlinear Sigma-point Kalman Filter from Chapter 11, Advanced Estimation Algorithms [7]. The Binary State Estimator employs 10 states for the dual body flyby: the 3-element correction vector to the center of the binary system, the apparent radius for each body, and 5 orbit states: inclination, ascending node, mean anomaly, major axis and mass ratio. Details of this implementation will be presented in a forthcoming paper.

Target Event Manager

As mentioned in the Instrument and Science Overview discussion, the spacecraft has a range-based sequencing capability. Due to surface resolution and surface area science requirements, shown in Table 1, and the large delivery uncertainties, shown in Figure 8, a purely time-based sequencing of IPP pointing and instrument imaging could result in science collection which does not meet the baseline requirements. Lucy implements a Target Event Manager (TEM) onboard software to sequence science instrument imaging activity and IPP pointing modes based on the spacecraft-to-target range estimate from the TTS. This range-based sequencing implementation, as shown in the flow diagram of Figure 16, allows the Lucy mission to maximize the science return of every image from the science instruments.

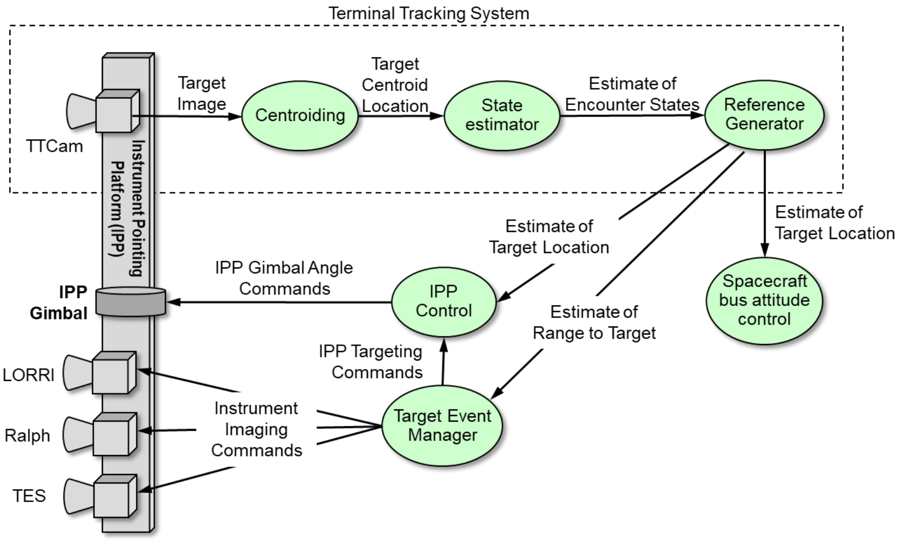

Figure 16: Target Event Manager integrates with Terminal Tracking System to perform range based commanding for instrument imaging and IPP pointing modes.

CONCLUSIONS

The Lucy Spacecraft will be the first mission to visit Jupiter’s Trojan asteroids and will flyby and obtain science from a record number of asteroids. The wide variety of targets being visited, and the unique aspects of each encounter, make designing a spacecraft and a mission concept of operations a challenge. A key factor in maximizing the quantity and quality of the science return to meet the mission requirements is the Terminal Tracking System, which employs centroiding and state estimation methods similar to other flyby missions, as well as novel range-based sequencing for pointing and science collection. The Lucy mission will be a long and exciting mission!

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