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Lucy's Encounter with Dinkinesh

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Abstract

NASA's Lucy mission to study the Trojan asteroids of Jupiter successfully encountered the main-belt asteroid (152830) Dinkinesh on November 1, 2023. Since its launch in October 2021, Lucy has spent most of its time in cruise, with occasional calibration campaigns for its science instruments. As the first asteroid flyby of the mission, the Dinkinesh encounter provided a natural end-to-end test of the uplink (observation planning) and downlink (data processing and archiving) tools and procedures developed by the Lucy Science Operations Center.

The Dinkinesh encounter was added to Lucy's schedule in January 2023, after it was realized that Lucy's trajectory at the time would already pass within 70,000 km of Dinkinesh. Although the Dinkinesh encounter was designed first and foremost as a test of the spacecraft's terminal tracking system, the Lucy SOC and instrument teams used their uplink planning tools to obtain images and spectra with Lucy's science instruments near close approach, revealing Dinkinesh's surprisingly complex shape and contact binary satellite (Levison et al. 2024). The success of these observations is remarkable because the planning timescale for the Dinkinesh encounter was far more compressed than for Lucy's Trojan asteroid encounters. These data were also used to refine the SOC downlink tools for producing uncalibrated and calibrated instrument data and to develop the archiving pipeline. In August 2024, Dinkinesh encounter data were delivered to the Small Bodies Node of the NASA Planetary Data System (PDS), where they are permanently archived. All data collected during Lucy's encounter with Dinkinesh were publicly released after passing PDS review.

Keywords: Lucy, (152830) Dinkinesh, Science Operations

Acronyms/Abbreviations

Instrument Pointing Platform (IPP)
Planetary Data System (PDS)
Science Operations Center (SOC)
Terminal Tracking Camera (TTCam)

1. Introduction

The Lucy mission, part of NASA's Discovery program, launched in October 2021 and is now enroute to the Trojan asteroids of Jupiter. Trojan asteroids reside in gravitationally stable orbits near a planet's L_4 and L_5 Lagrange points, and Jupiter's Trojans are believed to be captured planetesimals that formed in the outer regions of our Solar System's protoplanetary disk [1,2]. Lucy is the first mission designed to visit Jupiter's Trojan asteroids, with four flyby encounters in the L_4 Trojan swarm in 2027 and 2028, and an encounter with an equal-mass binary in the L_5 Trojan swarm in 2033 [3,4,5].

Before reaching its Trojan targets, Lucy will have two rehearsal encounters of main-belt asteroids [5]. The first encounter with (152830) Dinkinesh on November 1, 2023, is the subject of this paper. The second encounter with (52246) Donaldjohanson on April 20, 2025, is the subject of another paper in these proceedings [6].

2. A New Lucy Target

When Lucy launched, the flyby of Donaldjohanson[†] was the only rehearsal on the mission timeline [1]. However, the geometry of the Donaldjohanson encounter differs from Lucy's Trojan encounters in several important ways. In particular, the high phase angle on departure requires Lucy to point away from Donaldjohanson shortly before close

[†] The asteroid is named for the discoverer of the famous *Australopithecus afarensis* hominin fossil "Lucy". The Lucy mission is named after the fossil and hopes to shed light on the origins of our Solar System in the same way that "Lucy" shed light on human origins [1].

approach for sun avoidance, which means that this encounter is not an ideal test of Lucy's terminal tracking system [6], which autonomously determines the spacecraft's position with respect to the target during encounters [4].

Shortly before Lucy's first Earth Gravity Assist in October 2022 [7], it was realized that the spacecraft would pass within 70,000 km of the asteroid 1999 VD_{57}, subsequently named Dinkinesh‡. This proximity allowed Lucy to change course to fly within 425 km of Dinkinesh [5] without expending much fuel. Fortuitously, the Dinkinesh encounter geometry was also very similar to the geometries of Lucy's Trojan encounters. In January 2023, these considerations led NASA to add the Dinkinesh encounter to Lucy's docket as a test of the terminal tracking system.

3. Dinkinesh Observation Planning

Since the Dinkinesh flyby had a short development timeline, it needed to be a focused engineering test. Thus, the Lucy Science Operations Center (SOC) treated the Dinkinesh encounter as a cruise load rather than a science load.

Lucy spends most of its time in cruise, with occasional calibration campaigns for its science instruments: L'LORRI, a high-resolution panchromatic imager [8]; L'Ralph, a visible/near infrared multi-spectral imager and a short wavelength infrared hyperspectral imager [9]; L'TES, a thermal emission spectrometer [10]; and the Terminal Tracking Cameras (TTCam) [11], which were designed as engineering instruments but are sufficiently calibrated that they are also used for science [12]. The instruments are all mounted on Lucy's Instrument Pointing Platform (IPP), which is connected to the spacecraft by a two-axis gimbal [4]. This configuration allows the instruments to be positioned without changing the spacecraft attitude and is crucial for Lucy's terminal tracking system [4,5].

For cruise calibration campaigns, the commanding for each instrument is developed separately by SOC sequencers who work closely with the Instrument Teams to ensure that requirements are met. Once all instrument sequences are mature, the SOC load lead merges them and resolves any conflicts. The load lead is also responsible for running the SOC's uplink planning tools (e.g., the Science Encounter Sequence Simulator [13]) and coordinating with the Mission Operations Center at Lockheed Martin.

This same process was followed during Dinkinesh development. SOC instrument sequencers and the Instrument Teams worked together to develop Science Activity Plans to specify the commanding details for all observations. The SOC sequencers then implemented and reviewed the commanding for their instrument and the SOC load lead merged the instrument-specific sequences. Conflicts between instruments were minimized by the intentional lack of complexity in the sequence.

3.1 Differences between the Dinkinesh and Donaldjohanson encounters

The Dinkinesh and Donaldjohanson encounters are both rehearsals with main-belt asteroids that have no formal science requirements [3,4,5], but the similarities end there. Differences in their encounter geometries were discussed in Section 2 and [6], but there were also procedural differences in how the encounters were planned and developed.

From the beginning, the Dinkinesh encounter was developed as a cruise load, but the Donaldjohanson encounter started with an early draft of Lucy's encounter with (15094) Polymele, the most stressing Trojan encounter [6]. Since the Donaldjohanson encounter began with a science sequence, its early development used Measurement Techniques developed by the Science Team to satisfy requirements in the Project Level Requirements Appendix; see [6] for details.

Another important difference between the encounters involves IPP movements. The purpose of the Dinkinesh encounter was to test terminal tracking performance, so the SOC did not command any IPP movements. This restriction ensured that all IPP motion during the encounter was initiated by the terminal tracking system compensating for spacecraft motion to keep Dinkinesh centered in TTCam. For the Donaldjohanson encounter, the IPP is commanded by the SOC to perform mosaics, to point to a position that allows Ralph to cool on approach, and to point away from Donaldjohanson just before closest approach to ensure the instruments do not point too close to the Sun [6].

4. Dinkinesh and Selam

The Dinkinesh encounter brought several surprises. The first surprise was that Dinkinesh has a satellite, named Selam§, but arguably the biggest surprise of all was that Selam is a contact binary [14]. All instruments worked nominally, and their data yielded insights into the geology, surface composition, and thermal inertia of Dinkinesh and Selam; see [14] for details. We were particularly lucky that Selam was close enough to Dinkinesh near closest approach that it could be seen at high resolution (Fig. 1).

Despite the unexpectedly complex nature of Dinkinesh and Selam, the terminal tracking system worked flawlessly. When Dinkinesh and Selam were well-separated, terminal tracking detected both components and tracked the larger

‡ The asteroid's name comes from the Amharic word for the Lucy fossil, Dink'inesh, meaning "you are marvelous".

§ Selam is named for a juvenile *Australopithecus afarensis* hominin fossil that has been nicknamed "Lucy's baby". The word "Selam" means "peace" in Amharic.

Figure 1: TTCam images of Dinkinesh and Selam taken near closest approach. The apparent motion of Selam with respect to Dinkinesh is mostly the result of parallax from spacecraft motion.

one, Dinkinesh. When Dinkinesh and Selam were sufficiently close together, terminal tracking merged them into a single component and tracked their center of brightness. All in all, it's hard to imagine we could have contrived a better test of the terminal tracking system if we tried.

5. Dinkinesh Data Processing and Archiving

The SOC pipelines for producing uncalibrated and calibrated data were developed in conjunction with the Instrument Teams and used to successfully process data obtained during cruise calibration campaigns. However, some features only pertain to encounter data or can only be exercised when Lucy is sufficiently far from the Sun. For example, although developing a shape model for Dinkinesh was not required as part of the encounter, the Science Team exercised the process of doing so using L'LORRI and TTCam images. This exercise discovered inefficiencies with SPICE kernel management related to ground-system software freezes that resulted in incorrect trajectory reconstruction immediately after the encounter. These issues were resolved by rerunning the pipelines after updating the kernels and led to improved ground system procedures for subsequent encounters.

All Lucy data will be permanently archived at the Small Bodies Node[**] of NASA's Planetary Data System (PDS). The Dinkinesh encounter data comprised Lucy's first full PDS delivery and served as the basis for developing the SOC data archiving pipeline. This pipeline creates PDS4-compliant bundles for each instrument that contain raw and calibrated data collections (instrument data with XML labels) as well as calibration and documentation collections. Data collected during the Dinkinesh encounter were delivered to the PDS in August 2024. The instrument data bundles were reviewed in September 2024 and publicly released in October 2024. The final Dinkinesh data delivery addressing all reviewer liens is scheduled for April 2025.

6. Conclusions

Lucy's encounter with Dinkinesh was a resounding success. Observation planning by the SOC and Instrument Teams went smoothly and all instruments worked nominally throughout the encounter. The data returned contained several surprises, including the complex shape of Dinkinesh and the presence of its satellite, Selam, which is a contact binary. Despite these surprises, the terminal tracking system worked as expected. Data from the Dinkinesh encounter were used to update the SOC pipelines for producing uncalibrated and calibrated instrument data and to develop the data archiving pipeline. All Dinkinesh data were delivered to the Small Bodies Node of the PDS and were publicly released after passing PDS peer review.

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References

[1] A. Morbidelli, H.F. Levison, K. Tsiganis, R. Gomes, Chaotic capture of Jupiter's Trojan asteroids in the early Solar System, Nature 435 (2005) 462-465.
[2] D. Nesvorný, D. Vokrouhlický, A. Morbidelli, Capture of Trojans by Jumping Jupiter, The Astrophysical Journal 768 (2013) 45.

[**] Data archived with the Small Bodies Node can be found at https://pds-smallbodies.astro.umd.edu/.

[3] H.F. Levison, C.B. Olkin, K.S. Noll, S. Marchi, J.F. Bell III, E. Bierhaus, R. Binzel, W. Bottke, D. Britt, M. Brown, M. Buie, P. Christensen, J. Emery, W. Grundy, V.E. Hamilton, C. Howett, S. Mottola, M. Pätzold, D. Reuter, J. Spencer, T.S. Statler, S.A. Stern, J. Sunshine, H. Weaver, I. Wong. Lucy Mission to the Trojan Asteroids: Science Goals, Planetary Science Journal 2 (2021) 171.

[4] C.B. Olkin, H.F. Levison, M. Vincent, K.S. Noll, J. Andrews, S. Gray, P. Good, S. Marchi, P. Christensen, D. Reuter, H. Weaver, M. Pätzold, J.F. Bell III, V.E. Hamilton, N. Dello Russo, A. Simon, M. Beasley, W. Grundy, C. Howett, J. Spencer, M. Ravine, M. Caplinger, Lucy Mission to the Trojan Asteroids: Instrumentation and Encounter Concept of Operations, Planetary Science Journal 2 (2021) 172.

[5] C. Olkin, M. Vincent, C. Adam, K. Berry, J. Englander, S. Gray, H. Levison, J. Salmon, J. Spencer, D. Stanbridge, B. Sutter, Mission Design and Concept of Operations for the Lucy Mission, Space Science Reviews 220 (2024) 47.

[6] E. Birath, B. Keeney, J. Parker, J. Pineau, J. Salmon, I. Solanki, J. Spencer, Z. Talpas, M. Vincent, and the Lucy SOC, Lucy's Donaldjohanson Encounter Science Planning and Sequencing, Abstract #533, 18th International Conference on Space Operations, Montreal, Canada, 2025, 26 – 30 May.

[7] J.R. Spencer, J.F. Bell, P.R. Christensen, H.H. Kaplan, D.C. Reuter, A.A. Simon, H.A. Weaver, The First Lucy Earth Flyby (EGA1), Space Science Reviews 220 (2024) 3.

[8] H.A. Weaver, J.P. Wilson, S.J. Conard, J.D. Adams, S. Begley, J. Burgum, E.H. Darlington, N. Dello Russo, R. Hacala, S. London, M.F. Morgan, G. Murphy, T. Nelson, A. Shah, J.R. Spencer, H. Taylor, T. Boehmer, L. Burke, C. Drabenstadt, C. Henry, S. Ling, C. Porter, J. Yin, The Lucy Long Range Reconnaissance Imager (L'LORRI), Space Science Reviews 219 (2023) 82.

[9] D.C. Reuter, A.A. Simon, A. Lunsford, H. Kaplan, M. Garrison, J. Simpson, G. Casto, Z. Dolch, P. Finneran, W. Grundy, C. Howett, P. Kim, M. Loose, T. Null, F. Parong, J. Rodriguez-ruiz, P. Roming, K. Smith, P. Thompson, B. Tokarcik, T. Veach, S. Wall, J. Ward, E. Weigle, H. Levison, L'Ralph: A Visible/Infrared Spectral Imager for the Lucy Mission to the Trojans, Space Science Reviews 219 (2023) 69.

[10] P.R. Christensen, V.E. Hamilton, G.L. Mehall, S. Anwar, H. Bowles, S. Chase, Z. Farkas, T. Fisher, A. Holmes, I. Kubik, I. Lazbin, W. O'Donnell, C. Ortiz, D. Pelham, S. Rogers, K. Shamordola, T. Tourville, R. Woodward, The Lucy Thermal Emission Spectrometer (L'TES) Instrument, Space Science Reviews 220 (2023) 1.

[11] J.F. Bell III, Y. Zhao, E. Cisneros, M. Beasley, C. Olkin, M.A. Ravine, J.A. Schaffner, M.J. Clark, J. Shamah, P. Faiks, S. Mottola, C. Adam, E. Lessac-Chenen, B.J. Bos, The Terminal Tracking Camera System on the NASA Lucy Trojan Asteroid Discovery Mission, Space Science Reviews 219 (2023) 86.

[12] Y. Zhao, J.F. Bell III, E. Sahr, E. Lessac-Chenen, C. Adam, E. Cisneros, A. Winhold, M. Caplinger, M. Ravine, J. Schaffner, J. Shamah, S. Mottola, Pre-flight and in-flight calibration and performance of the Terminal Tracking Cameras (TTCams) on the NASA Lucy mission, Earth and Space Science 11 (2024) e2024EA003576.

[13] J.J. Salmon, D.E. Kaufmann, H.F. Levison, Simulating Lucy's Flybys of its Target Trojan Asteroids, Abstract #549, 18th International Conference on Space Operations, Montreal, Canada, 2025, 26 – 30 May.

[14] H.F. Levison, S. Marchi, K.S. Noll, J.R. Spencer, T.S. Statler, J.F. Bell III, E.B. Bierhaus, R. Binzel, W.F. Bottke, D. Britt, M.E. Brown, M.W. Buie, P.R. Christensen, N. Dello Russo, J.P. Emery, W.M. Grundy, M. Hahn, V.E. Hamilton, C. Howett, H. Kaplan, K. Kretke, T.R. Lauer, C. Manzoni, R. Marschall, A.C. Martin, B.H. May, S. Mottola, C.B. Olkin, M. Pätzold, J.W. Parker, S. Porter, F. Preusker, S. Protopapa, D.C. Reuter, S.J. Robbins, J. Salmon, A.A. Simon, S.A. Stern, J.M. Sunshine, I. Wong, H.A. Weaver, C. Adam, S. Ancheta, J. Andrews, S. Anwar, O.S. Barnouin, M. Beasley, K.E. Berry, E. Birath, B. Bolin, M. Booco, R. Burns, P. Campbell, R. Carpenter, K. Crombie, M. Effertz, E. Eifert, C. Ellis, P. Faiks, J. Fischetti, P. Fleming, K. Francis, R. Franco, S. Freund, C. Gallagher, J. Geeraert, C. Gobat, D. Gorgas, C. Granat, S. Gray, P. Haas, A. Harch, K. Hegedus, C. Isabelle, B. Jackson, T. Jacob, S. Jennings, D. Kaufmann, B.A. Keeney, T. Kennedy, K. Lauffer, E. Lessac-Chenen, R. Leonard, A. Levine, A. Lunsford, T. Martin, J. McAdams, G. Mehall, T. Merkley, G. Miller, M. Montanaro, A. Montgomery, G. Murphy, M. Myers, D.S. Nelson, A. Ocampo, R. Olds, J.Y. Pelgrift, T. Perkins, J. Pineau, D. Poland, V. Ramanan, D. Rose, E. Sahr, O. Short, I. Solanki, D. Stanbridge, B. Sutter, Z. Talpas, H. Taylor, B. Treiu, N. Vermeer, M. Vincent, M. Wallace, G. Weigle, D.R. Wibben, Z. Wiens, J.P. Wilson, Y. Zhao, A contact binary satellite of the asteroid (152830) Dinkinesh, Nature 629 (2024) 1015-1020.