AAS 24-191

LUCY OPTICAL NAVIGATION PERFORMANCE DURING THE (152830) DINKINESH ENCOUNTER

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The Lucy Jupiter-Trojan asteroid mission launched in November 2021. Its original mission concept included six small-body encounters over its 12-year primary mission. In the fall of 2022, an additional target of opportunity encounter was proposed to be executed in the fall of 2023. The encounter with (152830) Dinkinesh (previously 1999 VD57) presented myriad imaging, navigation, engineering, and planning challenges, as well as a chance to exercise and further refine the Optical Navigation System concept of operations, interfaces, and tools. Dinkinesh would be the smallest and dimmest target Lucy would encounter, with a higher uncertainty in these physical parameters than for other targets. While the OpNav system and instruments carried a high amount of heritage from the New Horizons and OSIRIS-REx missions, this would be the first use of these systems on Lucy for navigation purposes. Despite these additional challenges, the Lucy-Dinkinesh encounter was a resounding success throughout which the navgational system exceeded requirements.[1] Optical Navigation was successfully performed and fed into the orbit determination and trajectory maneuver activities up to the final knowledge update. The Dinkinesh encounter also proved to be greatly scientifically interesting, if not additionally challenging, as the Dinkinesh system was discovered to be a binary system through imaging during closest approach, and the secondary body was itself found to be a contact binary. This added complexity notwithstanding, the OpNav and OD teams were able to reconstruct the close-approach trajectory of Dinkinesh in cooperation and concert with the Lucy Science Team's shape modelling efforts.

INTRODUCTION

Mission Overview

The NASA Lucy Jupiter-Trojan asteroid mission launched on October 16th, 2021, to explore the Trojan asteroid clusters at the Jupiter-Sun L4 and L5 points. The original mission profile included a total of six small-body encounters: a dress-rehearsal flyby of the main belt asteroid (52246) Donaldjohanson (DJ) on its way out to the Trojans, four systems in the L4 Trojan cluster between June 2027 and November 2028, and one encounter with a binary system in the Trojan L5 cluster in 2033. With the discovery of small moons around Eurybates and Polymele, the number of possible close-approach imaging targets sat at 9 by fall of 2022. It was then that an additional encounter was

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proposed, that of the main belt asteroid (152830) Dinkinesh (previously 1999 VD57); the Dinkinesh encounter would begin less than 10 months later. Its eventual addition to the mission timeline can be seen in Figure 1

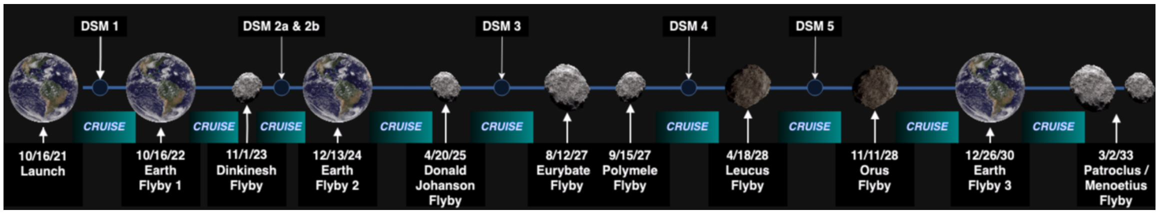


Figure 1: Mission Event Timeline After Addition of Dinkinesh Encounter

Optical Navigation System

A critical technology for achieving the required accuracy for the Lucy flybys is optical navigation (OpNav), a sub-function of the Flight Dynamics System (FDS). The mission navigation, including OpNav, is provided by KinetX Aerospace, with management and mission design support from NASA's Goddard Space Flight Center.[2]

The primary tool for OpNav on the Lucy mission is the KinetX Star-Based Image Processing Suite (KXIMP), which is utilized for star-based instrument pointing and centroid-based navigation. An additional suite of analysis tools were developed by the OpNav team to plan and pre-process images. Using only radio metric observations of the Jupiter Trojans for targeting each flyby would require greater flyby distances than can be acheived using OpNav. OpNav images taken from the spacecraft are used to more accurately determine the trajectory of the Trojan relative to the spacecraft, allowing for lower flyby closest approach distances. OpNav uses star-based navigation to determine precise instrument orientation. With this pointing solution, we exercise various center-finding algorithms on the target bodies in the images to arrive at a precise spacecraft-target vector direction.

The primary and sole OpNav imager on-board the Lucy spacecraft is the L'LORRI long-range reconnaissance imager.[3] L'LORRI is a high resolution, high dynamic range, small field-of-view instrument. The Lucy imagers all are mounted to a common two-axis articulated Instrument Pointing Platform (IPP). L'LORRI, like the OpNav Team, carries heritage from the New Horizons mission.

Because Lucy will perform a record number of small-body encounters over its mission, some within mere weeks of each other, a standard encounter timeline was developed as a starting off point for all encounter planning. It contains two Trajectory Correction Maneuvers (TCMs) that serve to refine the encounter targeting based on the orbit determination solutions on approach, and a Final Knowledge Update (FKU) of the spacecraft's target-relative trajectory four days before closest approach (C/A), which is used by the on-board sequence during C/A. As can be seen in Figure 2, during the Dinkinesh encounter, the subject of this paper, a communications blackout beginning at E-28 days required a modification to this TCM schedule to allow for contingency scenarios and sufficient tracking before tracking was lost.

The period from E-60 days to E-4 days is the period in which the primary OpNav processes are exercised to navigate the spacecraft through the encounter. An OpNav visit is defined as a set of OpNav images taken during a single spacecraft activity and used to produce a set of relatively closespaced observables. Lucy performs 3 OpNav visits a week for the first two weeks of an encounter, after which it switches to daily OpNav visits, with some exceptions to accomodate other spacecraft activities. Lucy continues these daily visits through E-5 days until the FKU. Additionally, daily imaging after FKU and through closest approach and departure, as well as much higher cadence resolved imaging during the inner 4 hours of the encounter, is used by OpNav to assist in the encounter trajectory reconstruction.

The OpNav Team designs its imaging schedules to provide 8 observables at every OpNav visit. This is done in order to sample image noise effectively and gives us a statistical measurement set for the orbit determination process. This helps us understand our performance and helps inform our data weighting. This also conveniently builds in extra conservatism to the OpNav plan, as this number can be reduced when necessary to increase the quality of individual observations because of an OpNav process called coadding. For dim targets coadding is often required to meet signal-to-noise (SNR) requirements for OpNav observables, and is part of the OpNav plan for 4 of the original 6 planned encounters. In this process, multiple images taken back to back are co-registered and then averaged in order to reduce the noise level and increase SNR. Analyses of predicted photometrics in order to determine the required number of coadded images is a key component to the OpNav planning process.

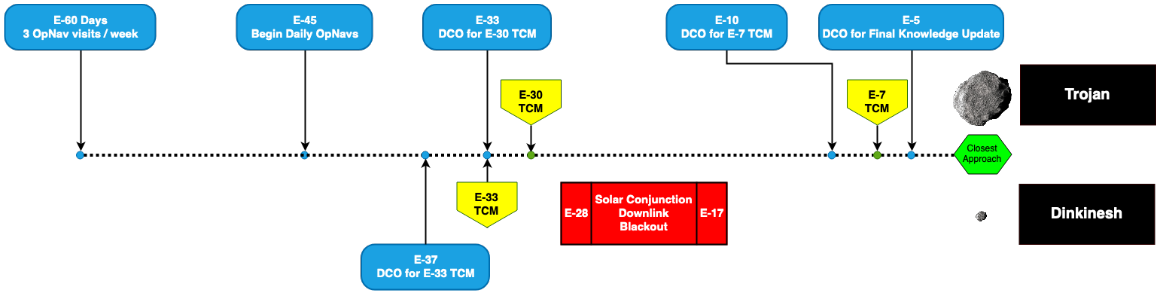


Figure 2: Encounter Timeline: Standard Trojan Encounter vs. Dinkinesh

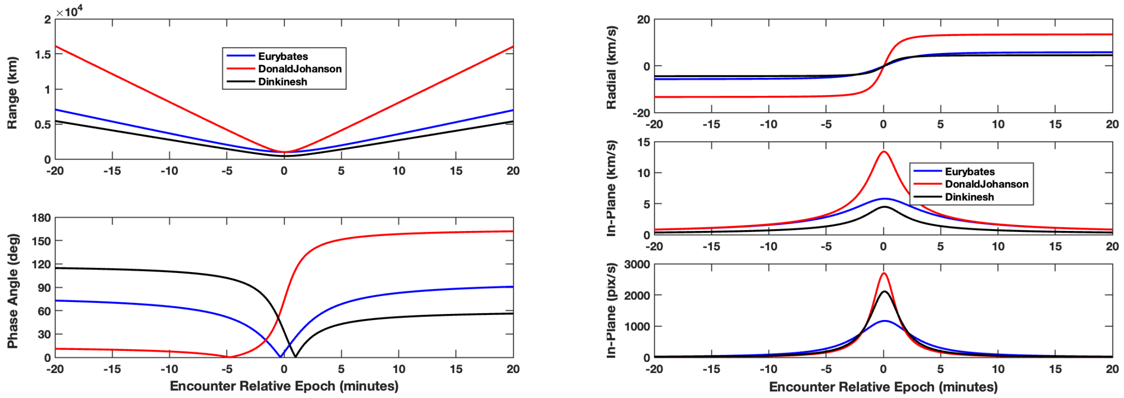
Terminal Tracking during Closest Approach

While OpNav is performed ground-in-loop from the start of the encounter until a final knowledge update uplinked four days before closest approach, in the final hours of the encounter an on-board Terminal Tracking Cameras system (TTCams) is responsible for controlling the IPP during the encounter. However, without this system, the uncertainty attached to the navigation solutions at the last onboard knowledge update opportunity five days before the encounter (E-5 days) would be too large to guarantee the target will remain within the field of view (FOV) of L'LORRI. TTCams have a much larger FOV than L'LORRI, but lower resolution resolution and dynamic range, making them well-suited to track the targets during closest approach.While the bulk relative motion of the target on the plane of sky is compensated for by spacecraft slewing during the encounter based on the final knowledge update (FKU) at E-5 days of the trajectory and ephemeris, the TTCams-controlled IPP makes smaller pointing corrections based on its own internal state estimator during closest approach. The success of an encounter rests on TTCams' ability to converge on a solution for the target and make the appropriate adjustments via the IPP to ensure successful imaging of the target by the L'LORRI instrument.[4]

Target of Opportunity Motivation

While in flight during the cruise period between two earth gravity assists, a target of opportunity presented itself. Soon after in February of 2023 the mission decided to perform an additional small-body encounter before all previously planned ones. On Nov 1st, 2023 the Lucy spacecraft flew by the main belt asteroid (152830) Dinkinesh (previously 1999 VD57) at a distance of 420 km. While the Optical Navigation System used for Lucy is derived from existing software that has been used on previous NASA interplanetary missions, the Dinkinesh encounter was the first use of the system on the Lucy mission operationally for spacecraft trajectory and small-body ephemeris determination.

Though Dinkinesh ultimately proved to be very scientifically interesting, the primary purpose of adding to the mission itinerary was to ensure as faithful as possible an engineering test of the TTCams system well before the first Trojan encounter. These system checkouts were intended to take place during the DJ encounter in 2025, however the Dinkinesh encounter proved to be a better test than DJ of these systems in the context of the Trojan encounters for a number of reasons, the primary one being the geometry of the encounter. The determinative geometric variables in an encounter for OpNav performance are the target phase angle, spacecraft-target range, and sun-target range at the imaging epochs. These, along with the physical characteristics of the target body, determine the apparent magnitude of the target, as well as its observable shape. For early encounter OpNavs, which are unresolved, the driving design factor is the apparent magnitude, however the TTCams system (which uses a different camera than that used for standard optical navigation and operates only within the inner 2 hours of closest approach) can be sensitive to the observable shape of the target. This shape, essentially the observable profile of the target, is in turn affected by the phase angle of the target. A higher phase angle shadows more of the object, is more sensitive to unmodelled shape features, and can change the performance of the TTCams system if not accounted for in testing. Looking at the geometry of the encounter from 20 minutes before to 20 minutes, shown in Figure 3, it's clear the geometry of the Dinkinesh encounter more closely resembles the Trojan encounters (as represented by the Eurybates encounter). Most importantly, Dinkinesh has a higher phase angle approach, crucial for correctly predicting TTCams acquisition and performance. Dinkinesh is also observable on departure, as are the Trojans, while DJ is almost completely in



(a) Position

(b) Velocity

Figure 3: Encounter Geometry Comparison for Trojan (Eurybates), Donald Johanson, and Dinkinesh Flybys

shadow on departure, making post-closest-approach reconstruction imaging infeasible. Dinkinesh also has an in-plane velocity that is closer to Eurybates, though the lower fly-by distance for Dinkinesh makes an angular measure of this velocity closer to that of DJ than of Eurybates.

Change Decision

A navigation feasibility analysis was done in December of 2022 to determine if the encounter could be navigated with minimal deviation from the standard encounter concept of operations (ConOps), as described in .[1] Dinkinesh's physical properties were not precisely known at that time, but it was clear that it was dimmer and smaller than DJ, which itself was already much dimmer and smaller than the Trojan targets. This would delay terminal tracking acquisition to much nearer to C/A than for a Trojan and further stress the approach optical navigation operations.

A covariance analysis[1] by the orbit determination team was performed to ensure the mission encounter requirements could be met for this range of possible target body physical parameters. We analyzed our capability to deliver the necessary OpNav products to achieve that performance by determining the target apparent magnitude, the signal-to-noise ratio (SNR) for given exposures, the necessary number of images to produce an OpNav observable, and the possibility of excessive interference of the background starfield affecting target center-finding performance.

DINKINESH ENCOUNTER FEASIBILITY ANALYSIS

Constraints and Uncertainties

Many natural and technical constraints were imposed on the initial analysis to assess the Optical Navigation feasibility of Lucy's encounter with Dinkinesh. Little was known about Dinkinesh at the time of the initial analysis other than it was small and dim; dinkinesh's spectral type, shape, size, and precise visual magnitude all had large uncertainties attached to them.[5] The phase angle of the approach was high and the sun-spacecraft range low, resulting in impingement of higher levels of solar stray light on the L'LORRI imager. Additionally, the downlink blackout mentioned in the previous section required careful data volume management in these OpNav analyses and plans.

Asteroid Spectral Type Uncertainties Early uncertainties in the spectral type required the Lucy Optical Navigation Team to analyze encounter feasibility for a range of potential Dinkinesh spectral types. These spectral difference lead to different predicted apparent brightnesses of Dinkinesh throughout the encounter, which in turn drove different requirements on the number of images needed in each coadded stack to achieve an observation with a signal-to-noise ratio of 7 or higher, the minimum requirement for OpNav observations. A dimmer Dinkinesh would require more images, compounding issues caused by constraints on data downlink.

As the analysis proceeded, the Lucy science team coalesced on a range of reasonable albedo and size assumptions for Dinkinesh which fed into the feasibility analysis, as shown in Table 1. These physical parameters were used to compute predicted absolute magnitudes for Dinkinesh, with an H-G photometry model[6] to predict the phase angle effects.

To fully analyze the range of potential apparent brightness scenarios, we assumed a worst-case scenario of a low albedo, small diameter Dinkinesh to assess feasibility – as this combination of physical factors would result in the dimmest apparent brightness of Dinkinesh throughout the encounter. However, analysis was also conducted using the 'Current Best Estimate' (CBE) of Dinkinesh's diameter and albedo to assess whether other constraint mitigations could be relaxed in the

		Albedo Case		
		Low = 0.25	CBE = 0.3	High = 0.35
Diameter	Large	850	780	720
	CBE	780	710	660
	Small	710	650	600

Table 1: Pre-encounter Potential Dinkinesh albedo and diameter ranges, including current best estimates (CBE)

event that further scientific analysis of Dinkinesh determined that the low albedo, small diameter case proved to be unrealistically conservative. A best-case brightness scenario was also analyzed to avoid oversaturating individual images if Dinkinesh proved to be bright.

The high phase angle of the encounter, as well as the smaller sun-spacecraft range than at the Trojans, resulted in higher levels of solar stray light impingement on the L'LORRI imager. This in concert with the already dim target presented an imaging challenge. While the solar stray light itself can be subtracted before center-finding, the noise associated with this signal can not. This additional noise decreases the signal-to-noise ratio (SNR), and thereby reduces the fidelity of each individual image. This reduction in performance thus necessitates coadding a greater number of images to produce an observation with an SNR of 7 or higher.

L'LORRI Solar Stray Light Impingement In order to mitigate this stray light on the L'LORRI imager, the L'LORRI instrument team proposed shielding the L'LORRI imager from the sun using the spacecraft bus. This required slewing the spacecraft into a special shading orientation at each OpNav visit and then slewing back afterwards, a novel attitude plan for Lucy which would require substantial effort on the part of the Lucy thermal team to assess impacts to spacecraft safety and longevity, as well as additional work to develop and sequence the slews. Because of these high development and analysis costs, one of the early goals of the OpNav encounter feasibility analysis was to assess whether this novel attitude was truly necessary for the encounter plan to close successfully. It quickly became clear that the shielding would be necessary for the majority of the encounter, though when that period would end was not yet determined. A cutoff date for shielding 18 days before closest approach was established to allow the thermal team to focus their efforts epochs where L'LORRI truly required it. As seen in Figure 4, all cases closed with 8 observables after this date, regardless of L'LORRI stray light. Later in development the determination of this cutoff date was revisited and modified, as discussed in the Dinkinesh OpNav Schedule Planning section.

During the proposed 60-day approach to Dinkinesh Lucy would enter into solar conjunction for a period of eleven days, during which the Lucy spacecraft would be unable to communicate with the Earth and creating a data downlink blackout. The spacecraft would exit conjunction only 16 days before closest approach, presenting a potential hazard for the OpNav plan. OpNav images taken between October 4th and October 15th would have to be stored on-board until after conjunction. This image backlog, along with new daily opnavs, would need to be downlinked and processed before the data cutoff for the final encounter targeting TCM, a cutoff just 6 days after Lucy exited conjunction.

Solar Conjuction Downlink Blackout To mitigate the impacts of this constraint, the Lucy OpNav team considered the use of L'LORRI's 4x4 binning mode. This function sums the raw data count from a 4x4 grid of pixels into 1 super-pixel on-board the spacecraft. While this reduces the resolution of the image, the tradeoff is an increase in SNR and a decrease in the data volume of each image, reducing the number of required images as well as the overall data budget of the images. Despite the benefits, the use of the 4x4 mode is not in the nominal Optical Navigation con-ops due to the degraded fidelity of these observations and was considered only for closing the case in the event of an unrealistically worst case photometry scenario.[2]

Photometric Cases

After many iterations, the Dinkinesh Encounter Feasibility Analysis converged on 5 OpNav cases, each considering different combinations of exposure times, stray light shielding, and Dinkinesh photometry possibilities. All five cases assumed the same encounter geometry, telecom constraints, conjunction dates, and navigation data cutoffs. Analysis for the encounter was broken out into a daily cadence for all cases, with analysis assuming all images taken in precisely 24-hour increments from the time of closest approach.

For the purposes of this initial feasibility analysis, other details that could negatively impact the encounter plan, such as smear due to Dinkinesh apparent motion from the first to last coadd image, and the bimodal L'LORRI point spread function, were not considered.

Feasibilty Analysis Results

A graphical summary of the results of this feasibility analysis appear in Figure 4. For every OpNav epoch, the number of coadds necessary to achieve a single OpNav observable is shown. Given this number of images per observable and the downlink data budget per DSN pass, the maximum feasible number of observables per OpNav visit for each epoch, as well as the size of the image downlink backlog caused by the solar conjunction period, whose span is shown in gray.

Case 1 assumes Dinkinesh to be an S-type asteroid. It also assumes L'LORRI is able to be shielded from solar stray light throughout the entire encounter. 30-second exposures are used through the entire encounter, when Dinkinesh is unresolved in the L'LORRI imager. This case closes well. Figure 4(a) shows that only 3 images per observable are required at the beginning of the encounter through E-51, dropping down to 2 imagers per observable through E-38, after which coadding is no longer necessary for the remainder of the encounter. Figure 4(b) shows that 8 observables per day is feasible for the entire encounter. The backlog that develops in this case during the solar conjunction is small, and able to be downlinked within 3 days of Lucy exiting the solar conjunction, as shown in Figure 4(c). It should be noted that the Case 1 line in Figure 4(c) sits underneath the Case 4 line, with identical backlogs in both cases exiting the solar conjunction.

Case 2 also assumes Dinkinesh to be an S-type asteroid. In this case, the L'LORRI imager is not shielded at all, resulting in substantial reductions in SNR due to solar stray light impingement on L'LORRI. This scenario does not close, with dozens of images required for one observable as shown in Figure 4. In fact, the spacecraft cannot even successfully downlink one full OpNav observable each day until E-44. The spacecraft cannot downlink the nominal 8 observables per day until E-15 days, as shown in Figure 4(b). For most of the encounter, the exposure time must be 60 seconds, increasing risk of reduced-fidelity data due to spacecraft pointing stability, and increasing risk of saturation should Dinkinesh be brighter than expected. This case was analyzed to justify the effort for analyzing the novel spacecraft attitude for this encounter.

Case 3 was designed as the Worst Case scenario for the Dinkinesh photometry, assuming that it is the smallest diameter and lowest albedo that the Lucy Science team thought to be reasonably possible at the time. L'LORRI is assumed to be shielded by the spacecraft bus in this scenario. In this case, a combination of 1x1 and 4x4 images are taken at 20- and 30-second exposures throughout the encounter in order for this case to close from a telecom perspective. The spacecraft is able to capture and downlink in a reasonable timeframe at least 4 observables per day worth of images, and can downlink 8 observables per day throughout most of the encounter, as seen in Figure 4(b). However, the use of L'LORRI's 4x4 mode was not in the nominal OpNav ConOps for any encounter in the Lucy mission, and the reduced fidelity of these observations resulted in a preference for 1x1 images unless absolutely necessary.

Case 4 assumes Dinkinesh to be a V-type asteroid, with a marginally brighter apparent magnitude than the S-type cases. This case uses 30-second exposures and assumes L'LORRI is shielded throughout the encounter. This cases closes well. Early encounter coadding only requires 3 images per observable through E-55days, dropping to 2 images per observable through E-40days. Coadding is no longer necessary after E-40days, as shown in Figure 4(a). 8 observables are feasible during every day of the encounter, as shown in Figure 4(b). A small backlog of 96 images develops during the solar conjunction as shown in Figure 4(c), which is able to be downlinked within 3 days of Lucy exiting the solar conjunction.

Case 5 assumes Dinkinesh to be a V-type asteroid. This case assumes L'LORRI to be unshielded throughout the encounter. As with Case 2, many early epochs result in 0 OpNav observables within the telecom constraints due to the very large number of images required for each observable, as shown in Figure 4(a) and 4(b). In order to clear the large backlog that accumulates through the solar conjunction communications blackout, there are many epochs with 0 images shuttered in order to downlink all of the necessary data in time for the navigation data cutoff, as in Figure 4(c). In fact, the analysis showed that some epochs prior to the solar conjunction could not shutter OpNav images in order to downlink all images taken during other non-conjunction epochs. As with case 2, this case was analyzed to justify the novel effort on the part of the Lucy thermal team to analyze the novel attitude that would facilitate the usage of Cases 1, 3, or 4.

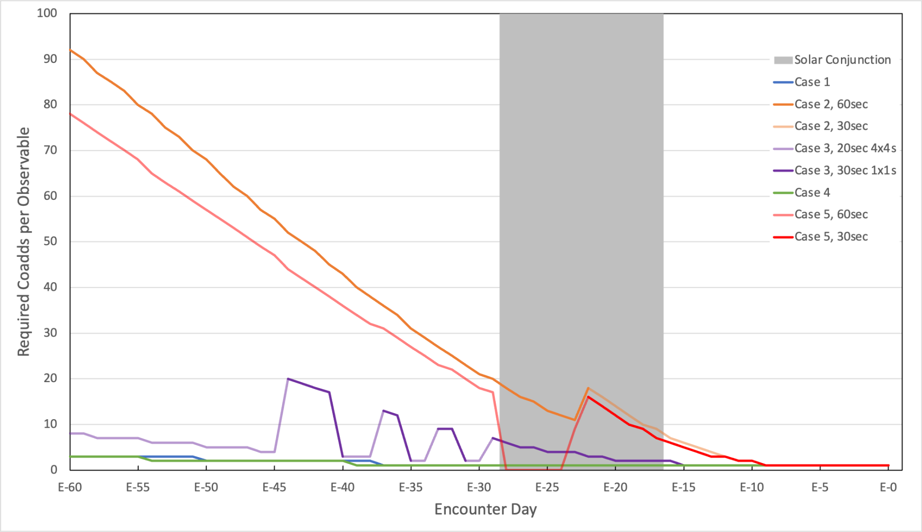
Feasibility Determination

The Dinkinesh encounter feasibility analyses showed that, with proper solar stray light mitigation and making use of the high data rates available, Lucy could successfully navigate the encounter within mission requirements.

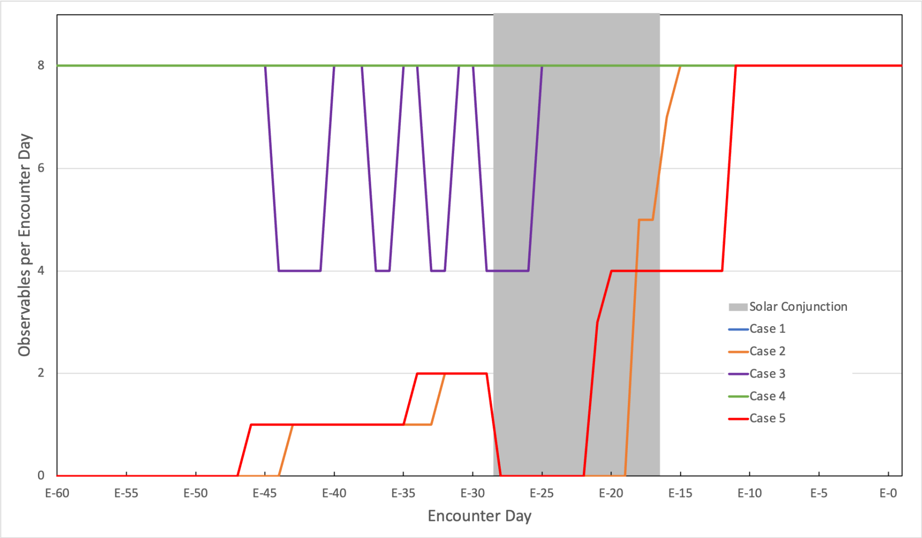
With these considerations and after careful analysis, the change decision was made and Dinkinesh was added as the Lucy mission's first small-body target. The late-breaking nature of the Dinkinesh opportunity discovery and decision significantly compressed the planning timeline, condensing a multi-year planning process into less than 9 months between the decision to go to Dinkinesh and the beginning of the encounter.

DINKINESH OPNAV SCHEDULE PLANNING

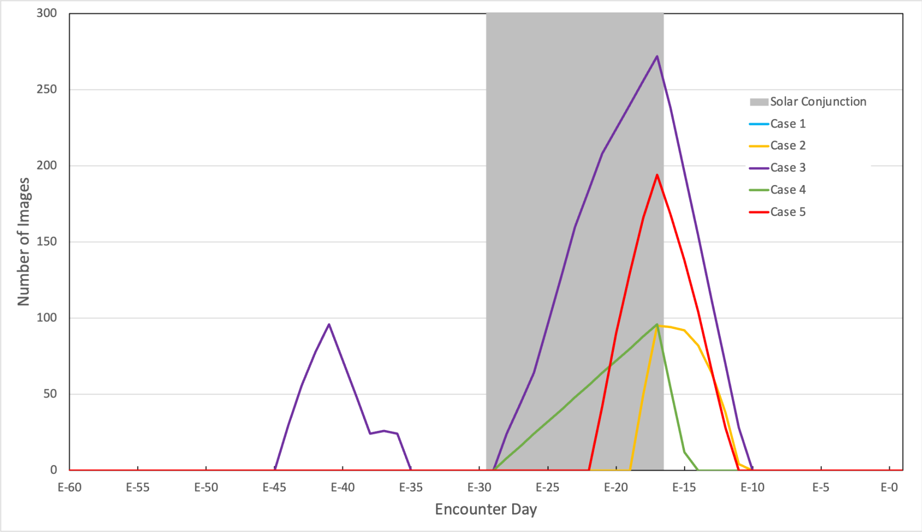
The OpNav planning process began with the feasibility analysis results, which showed the encounter could be navigated. Using the same tools as that analysis, an initial encounter design was arrived at based on a number of additional design parameters.



(a) Required # of Images per Observation for SNR=7



(b) Feasible Number of OpNav Observables per Visit



(c) On-Board OpNav Image Backlog Due To Solar Conjunction

Figure 4: Feasibility Analysis Results

During the sequence development, the date when L'LORRI would no longer be shaded was pushed later to after the final knowledge update, as the addition of the slews was found not to greatly impact the sequencing process or spacecraft performance for all imaging in that period.

Data volume limits were not very stringent for this encounter due to the higher data rates at Dinkinesh than can be expected later from 5 AU at the L4/5 clusters, however the dimmer target did stress the cases more than typical for a standard Lucy Trojan encounter.

An additional consideration motivated by the coadding algorithm drove the decision to keep the number of images in a stack to an odd number. The coadding algorithm registers all images in a stack to a reference image chosen from the stack and uses the epoch of that image for the stack observable. Because of this, it is preferred to use odd numbers of images in each stack to keep the images symmetric in time around the observable epoch.

Lastly, some additional shorter exposures were added from E-10 days forward to provide some data in the exposures that would be used during a Trojan encounter. During this period OpNav downlinks were well below the data constraints, and these additional images did not adversely affect the downlink budget.

With these considerations in mind, a nominal opnav schedule was arrived at, as shown in Figure 5. This schedule was then iterated upon with the spacecraft and sequencing teams to deconflict with other spacecraft activities such as momentum wheel desaturations, DSN downlink schedules, communications degradation from the solar conjunction period, and other conflicting activities.

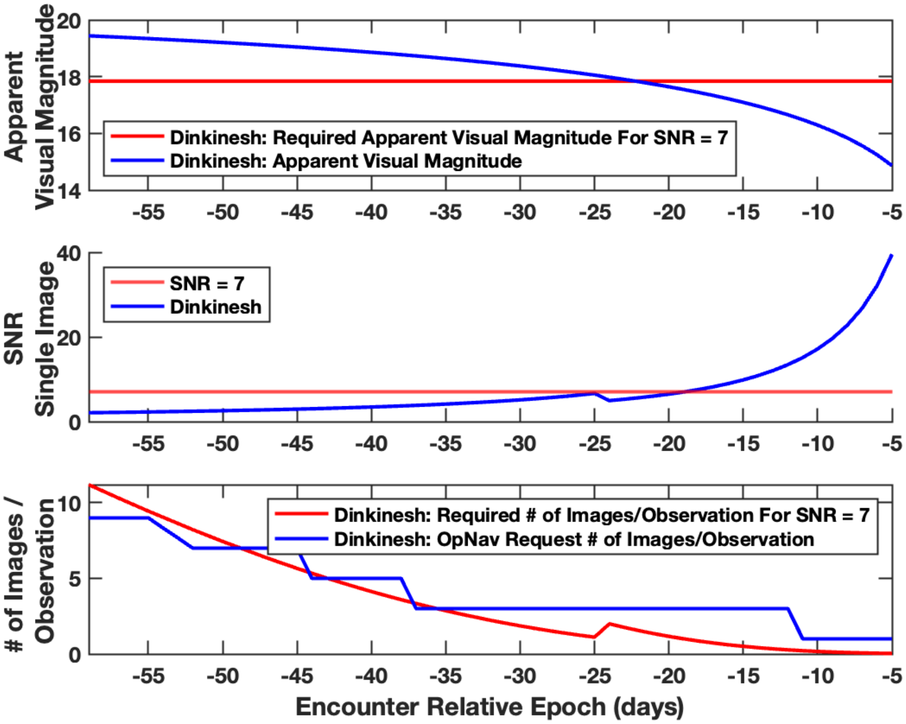


Figure 5: Sequenced number of images per observation compared with that required for SNR = 7

Additionally, an analysis of the background starfield during imaging epochs flagged spans in time when OpNav performance might be affected by interference from stars with brightnesses comparable or brighter than that of Dinkinesh. This analysis would be repeated again as Lucy approached the neighborhood of Dinkinesh, as it is limited by the trajectory uncertainties at the time of analysis mapped to the encounter epochs, and thus presents an overly grim picture when performed too early.

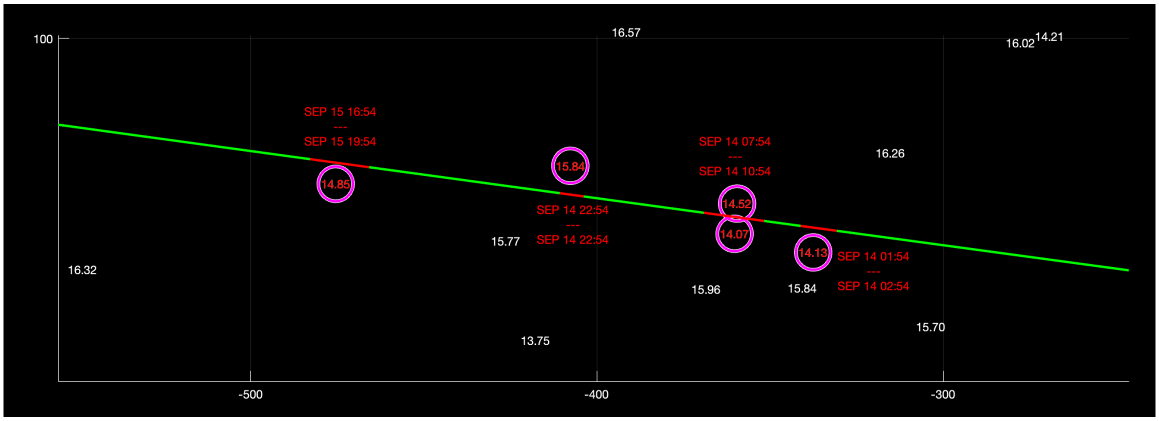


Figure 6: Design Encounter Starfield Deconflicting: target trajectory on the plane of sky, with possible bright background star conflicts shown in red with the corresponding conflicting epochs.

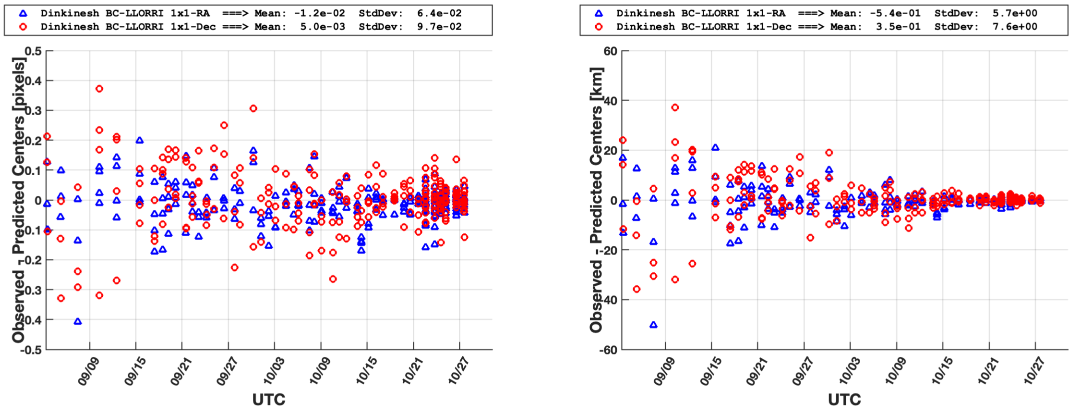
The OpNav team also worked in collaboration with the instrument and science teams to develop a range-based exposure time table to command TTCam's close-approach exposures. The TTCam exposures were important to tune well so that the terminal tracking system did not make false identifications from overexposures, or miss identifications from underexposures. These exposures did not affect the OpNav plan or performance leading up to the final knowledge update.

UNRESOLVED TARGET OPNAV RESULTS

Lucy began OpNav imaging 59 days before closest approach. From these images it was clear Dinkinesh was appearing dimmer than expected, perhaps by up to a factor of 3. The upper (dim) bound on the apparent magnitude of the Dinkinesh pre-encounter, before spacecraft-based imaging began, was thought to be 17.67, though there were quite a few questions from the then known ground-based light curve and the uncertainty attached to these estimates was not well known. Dinkinesh was already a dim target compared to other Lucy targets, and this correction to the photometric parameters further stressed the OpNav case. Additionally, it became clear in the ensuing days that the ground-based and spacecraft-based light curves told what seemed to be different stories; stories that would be illuminated later in the encounter by the discovery that Dinkinesh was a binary system of a very interesting nature.

At this point, it was decided to re-evaluate the coadding strategy to ensure the OpNav observables met performance requirements. This necessitated a reduction in the number of observables per visit for much of the encounter, however as previously noted, this did not adversely impact the navigation performance due to conservatism built in to the OpNav schedule. Converting the signal of a target in an image into a visual magnitude in order to reevaluate OpNav schedule can be a complicated endevour that is coupled with other physical target characteristics, instrument performance, and lighting conditions. However in an operational setting we can also base these strategies on input from the L'LORRI and science teams, analysis of OpNav residuals, and previous mission experience, as was done in this circumstance.[7]

In this re-engineered OpNav coadding strategy, three cases were processed in the early encounter, the originally planned case, a case which roughly doubled the number of images in each coadd, and one in which all images from each visit were coadded into one observation. These were eventually refined to one cohesive unresolved OpNav case of observables which were used by the Orbit Determination Team in Its trajectory solutions. As the post-fit target-center residuals show in Figure 7, the OpNav case converged steadily as we went into the FKU. Large OpNav residuals are expected in the early encounter when the target was dim and OpNav uncertainties can be higher. As Lucy approaches the FKU however, we see post-fit residuals of approximately 0.1 pixels, a level of precision expected from LORRI heritage, or on the order of 2 km. These results contributed to the high level of confidence the navigation team had in the trajectory of Lucy as it made its final approach.[1]



(a) Pixel Scale

(b) Kilometer Scale

Figure 7: Post-Fit OpNav Target Center Residuals: Final Knowledge Update (E-5 Days)

DINKINESH ENCOUNTER RECONSTRUCTION

Following the final ephemeris knowledge update, the on-board terminal tracking system was responsible for estimating the position of Dinkinesh relative to the spacecraft and ensuring that Dinkinesh remained in the L'LORRI FOV throughout the flyby. TTCams performed very well,[8] enabling imaging of Dinkinesh by L'LORRI for the entirety of the encounter. This produced a fruitful and informative set of images of Dinkinesh that would not only be used for scientific analysis but also for optical navigation reconstruction of the Lucy spacecraft trajectory and Dinkinesh ephemeris during the closest hours of the encounter. It was also discovered that a satellite of Dinkinesh, named Selam (itself a contact binary), was visible in a large majority of these flyby images. However, while the team has done some preliminary analysis and centerfinding of Selam, the optical navigation and science teams are still analyzing and estimating Selam's position as of the writing of this paper. As a result, only Dinkinesh center results are presented.

Many images containing Dinkinesh were captured during the inner most 4 hours (+/- 2 hours) around closest approach. The full imaging schedule, exposure times, and imaging cadence for the L'LORRI images acquired around closest approach are shown in Figure 8.

The images were taken in sets of 2 or 3, where both a longer and shorter exposure image was captured within a few seconds of one another. This was typically done to both provide conservatism

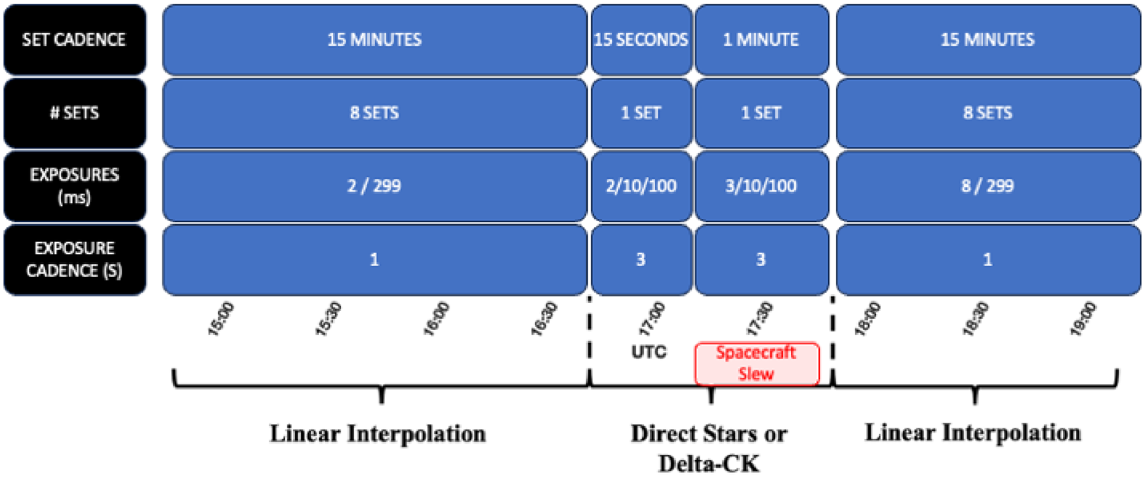


Figure 8: Dinkinesh Closest Approach Imaging Regimes

in the imaging plan, but also to capture a well-exposed image of Dinkinesh in the shorter exposure along with a well-exposed image of background stars in the longer exposure. The long-exposure image of background stars would allow for determination of the L'LORRI camera attitude at the image time, which could then be used to compute the attitude of the short-exposure image of Dinkinesh. In some cases, background stars were visible in the short exposure images of Dinkinesh, which allowed for direct attitude determination of the image attitude. In total, there were three types of attitude determination methods that were used to compute the image attitudes of the short-exposure images of Dinkinesh:

1. ***Direct attitude determination using stars in the image.*** This method is the most straightforward in that the short exposure image attitude is determined directly using visible stars in the image. This is the standard attitude determination method when both the target and stars are visible and well exposed in the image.

2. ***Linear interpolation between two long-exposure stellar images.*** This method computes the attitude of the short exposure image by linearly interpolating between two long exposure images, captured before and after the short exposure. This requires images to be taken in relatively quick succession (a few seconds) one after another. This method assumes that the attitude moves linearly between the long-short-long image sets, which was a reasonable assumption for the Dinkinesh reconstruction images taken when the spacecraft wasn't slewing quickly.

3. ***Delta-attitude computation using reconstructed spacecraft attitude telemetry (Delta-CK).*** This method computes the attitude of the short exposure image by rotating the estimated attitude of the nearest long exposure star image by the measured change in attitude between the long and short exposure image times, as determined by the on-board GNC system and corresponding telemetry. This method is colloquially called the "Delta-CK" method, since it applies the delta-attitude from long to short exposure as reported in the reconstructed SPICE[9] attitude C-Kernel (CK). This method was used when both direct attitude and linear interpolation could not be used, due to lack of visible stars causing gaps in image attitude solutions,

as well as very large spacecraft slewing during the inner-most closest approach, causing this method to be more robust than linear interpolation.

As was expected, stars were not detectable in every short or long exposure during the inner most closest approach imaging, due to various factors and artifacts such as lighting geometries, frame transfer smear, stray light and others. Thus, only a subset of the total number of images captured and presented in Figure 8 could be used for attitude determination and optical navigation reconstruction. In some cases, the spacecraft slew rate was fast enough to produce streaked star signals in some images, which provided a challenge for the star centerfinding and attitude determination algorithms.[10, 11] Nonetheless, the algorithm was tuned to accurately compute the centers of the streaked stars, albeit with higher uncertainties than typical star centerfinding solutions. In all, 209 images were used for attitude determination, which allowed 149 resolved images of Dinkinesh to be used for astrometry and optical navigation. Figure 10 identifies the periods when each of the three attitude determination methods were used.

Determining the centers of Dinkinesh in the images within $\pm$ 2 hours around closest approach was fundamentally different than centerfinding during the approach and departure, due to the fact that Dinkinesh was resolved ($>$ 3 pixels) during the closest approach. This required several methods and steps to ultimately compute reliable Dinkinesh centers with acceptable accuracy.

The first step was to determine the centers of Dinkinesh by cross correlating an illuminated sphere with the Dinkinesh signal in the image. The sphere was illuminated using the relative lighting geometry computed from the best estimate of the Dinkinesh, Lucy and Sun ephemerides, and represented a simulation of what Dinkinesh would look like if it were a perfect uniform sphere with a diameter that approximately resembled Dinkinesh's real average diameter. The centers computed by cross correlating Dinkinesh with an illuminated sphere was known to have relatively large errors and biases, but it was determined that this method would be the current best method over other options like a moment algorithm or manual centerfinding by eye. These Dinkinesh centers were then used to estimate an update to the Lucy flyby trajectory and Dinkinesh ephemeris, which was then delivered to the Lucy science team for further analysis.

The next step in the reconstruction process was for the science team to construct a 3D shape model of Dinkinesh, which would be used to improve the Dinkinesh centerfinding performance. The science team used many images around the encounter to construct a reliably accurate shape model of Dinkinesh, which OpNav made use of to cross-correlate against the real images of Dinkinesh. A sample image of Dinkinesh along with a simulation of the illuminated shape model used for cross-correlation is shown in Fig. 9. The observed center determined by the cross-correlation, as well as the predicted Dinkinesh limb outline is also provided in Fig. 9.

Reprocessing the Dinkinesh target centers using the 3D shape model cross-correlation proved to significantly improve the observation accuracy and precision. The Dinkinesh center residuals computed by this improved method are provided in Figure 10. As shown in the metric-space residual plot, the precision of the measurements allows for precise orbit determination of the Dinkinesh and Lucy ephemerides, which is currently still under analysis as of the time of this paper.

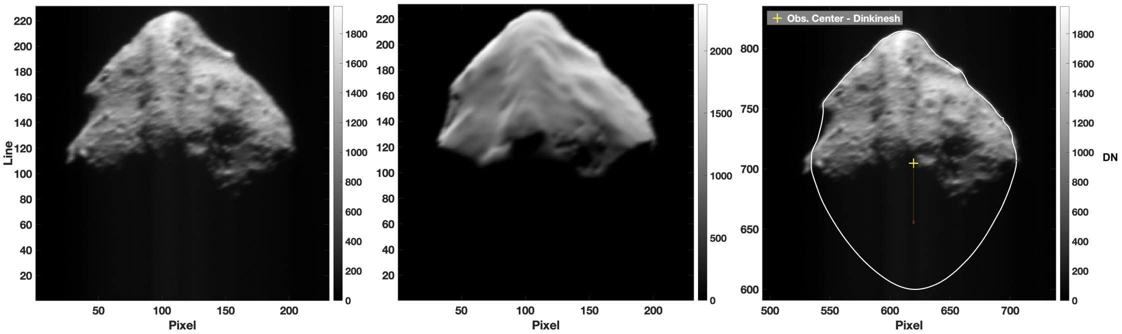


Figure 9: Left: Image of Dinkinesh as captured during inner closest-approach using the L'LORRI imager. Center: Corresponding simulated image of Dinkinesh using the 3D shape model of Dinkinesh and representative illumination geometry. Right: Real image of Dinkinesh overlaid with the observed center of Dinkinesh as computed using a cross-correlation between the real and simulated images of Dinkinesh. The white outline represents the simulated limb of Dinkinesh as computed using the shape model centered at the observed center, and the red arrow represents the direction of solar illumination.

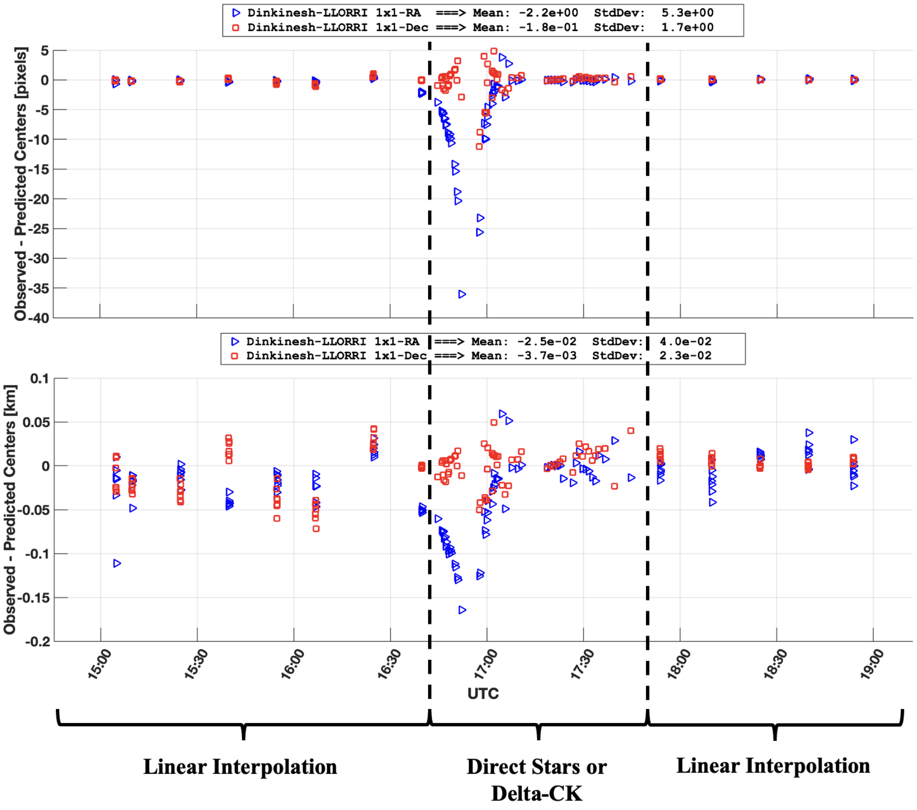


Figure 10: Dinkinesh Right Ascension (blue) and Declination (red) center residuals with respect to orbit determination solution OD051, in units of pixels (top) and kilometers (bottom), for the inner closest-approach period on November 1, 2023. The periods when each type of attitude determination method were used are identified.

CONCLUSION

The Dinkinesh encounter represented a resoundingly successful test and dress-rehearsal of Lucy's encounter systems, including the Optical Navigation system, the Terminal Tracking system,[8] and the myriad mission interfaces required for successful encounter development, execution, and analysis.

The OpNav system performance exceeded expectations, with target center residuals on the order of a tenth of a pixel at the final knowledge update five days before closest approach. The precision of the optical navigation during closest approach of a fast-moving target of uncertain physical parameters allowed the Lucy Science teams to quickly develop a shape model of Dinkinesh. This model was used to improve the OpNav target center solutions for a refined trajectory solution.

Despite no science requirements for this engineering-driven encounter, the exciting and informative discovery of not only a binary system, but one containing a contact binary as the secondary object was made under difficult imaging conditions. In the coming months, attempts at a shape model of the secondary object, a bi-lobal contact binary, and an orbit solution for the binary system will be made with the limited data available for those estimations.

Many lessons were learned and new developments made to the approach OpNav systems, concept of operations, and technical tools during the planning and execution of the Dinkinesh flyby, lending to an incredibly well-prepared team and spacecraft for the upcoming DJ and Trojan encounters. A deep analysis of the pointing behavior of the spacecraft and the Instrument Imaging Platform (IPP) led to improvements in OpNav ConOps during reconstruction, including refinement of the exposure planning strategy to optimize pointing solutions more effectively, and additional opnavs to make up for degraded pointing performance during post-encounter spacecraft slews. The encounter has also lent motivation to additional work modelling the L'LORRI PSF before future encounters in order to increase the fidelity of the OpNav analyses and exposure planning.

The interfaces between the OpNav and Spacecraft Teams were also improved upon and better documented through this encounter, leading to more efficient deconflicting of the OpNav schedule with spacecraft activities and DSN schedules.

And importantly, the Dinkinesh encounter demonstrated the Lucy Terminal Tracking systems capability to successfully point the craft and keep the target within the LLORRI FOV for close approach imaging, a task it accomplished in a more difficult imaging environment than it will find at the Trojans.

ACKNOWLEDGMENT

The author's would like to thank Lucy Science and L'LORRI Teams for their work on characterizing the properties and performance of Dinkinesh and the L'LORRI imager, and Stefano Mottolo of the Institute of Planetary Research at the German Aerospace Center (DLR) for the development of the Dinkinesh shape model.

The work done by the OpNav team was also made possible through the collaboration of the entire Lucy Operations Team in planning and executing a successful encounter.

This work is supported by NASA under Contract 80GSFC18C0070. Lucy is the 13th mission in NASA's Discovery Program. Hal Levison of the Southwest Research Institute (SwRI), is the principal investigator. Lockheed Martin Space Systems in Denver built the spacecraft and is providing flight operations. Goddard Space Flight Center and KinetX Aerospace are responsible for navigating the Lucy spacecraft.

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