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ORBIT DETERMINATION FOR LUCY'S FIRST ASTEROID ENCOUNTER: THE DINKINESH (1999VD57) FLYBY

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Lucy, NASA's 13th Discovery program mission, launched on October 16, 2021, is en route to explore the Jupiter-Trojan asteroids situated at the L4 and L5 Lagrange points. Along this trajectory, Lucy will conduct flybys of two main belt asteroids and perform three Earth flybys. This paper delves into the Orbit Determination (OD) process during the Dinkinesh flyby, marking Lucy's inaugural encounter with an asteroid. The Dinkinesh flyby achieved a significant milestone, flawlessly completing the engineering systems checkout. The discussion herein encompasses the OD strategy, setup, and computed OD solutions during operations. The paper further explores the impact of solar conjunction on the OD solutions and decisions and sheds light on the discovery of Selam, a contact binary orbiting Dinkinesh. Preliminary reconstructed trajectories for both Lucy and Dinkinesh, and an initial state of Selam, are presented. The close approach radial distance of Lucy from Dinkinesh was 430.63 km $\pm$ 0.02 km in formal uncertainty.

INTRODUCTION

Lucy, NASA's 13th mission in the Discovery program launched on October 16, 2021 on an Atlas V 401 from space launch complex 41 at Cape Canaveral, Florida. The main objective of the mission is for Lucy to visit the Jupiter-Trojan asteroids located at the L4 and L5 Lagrange points, which have never before been visited.[1] The first of nine Trojan asteroid encounters is Eurybates in August of 2027 located in the L4 region. However prior to the main mission objectives, two main belt asteroids Dinkinesh and Donaldjohanson have flybys to perform engineering checkouts of Lucy's systems and prepare the team for encounter operations. Dinkinesh was not part of the original mission itinerary, unlike Donaldjohnason, but because the original trajectory was going to flyby Dinkinesh at 64,000 km anyway, only a small trajectory correction was needed to include this additional target.[2] By adding Dinkinesh, the checkout of Lucy was now a year and a half earlier, moving up from April 2025 for the Donaldjohanson flyby to November 2023 for the Dinkinesh flyby. Recall that within hours of launch the spacecraft team discovered that the +Y solar array did not fully deploy and latch, while a series of re-deployment attempts were executed, the solar array has not latched. If Lucy encounter science was going to be degraded, due to the unlatched solar array, it was best to find out as early in the mission as possible thereby maximizing the available time to find and implement a solution prior to any Trojan encounters.

Fortunately, the Dinkinesh encounter was a resounding success for the Lucy mission and team. This paper will cover the orbit determination (OD) perspective of the Dinkinesh flyby. The discussion first includes an

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overview of the operations schedule and important activities leading up to the flyby. This is followed by the OD strategy and filter setup. Next, we discuss the operational OD solutions, and finally we cover the reconstructions of the Lucy and Dinkinesh ephemerides as well as an initial state for Selam. This paper discusses the OD operations, analysis, and initial findings during and immediately after the Dinkinish flyby. The results presented here are preliminary and the navigation team expects to iterate with the science team to refine the reconstruction as we get improved shape data.

DINKINESH FLYBY OVERVIEW

In early 2023, the project officially decided to add the Dinkinesh asteroid encounter to the list of targets with a flyby date of 1 November, 2023. Figure 1 illustrates the orbit and major events from 2022 to 2024, on this scale there is no noticeable difference in the trajectory that includes and does not include the Dinkinesh flyby. Following the first Earth Gravity Assist (EGA) on October 16, 2022 Lucy's aphelion was kicked out past 2 AU where the main belt asteroid Dinkinesh would catch up and fly by Lucy before the largest mission maneuver of DSM2 and the spacecraft falls back toward the Sun for its next EGA on 12 December, 2024.

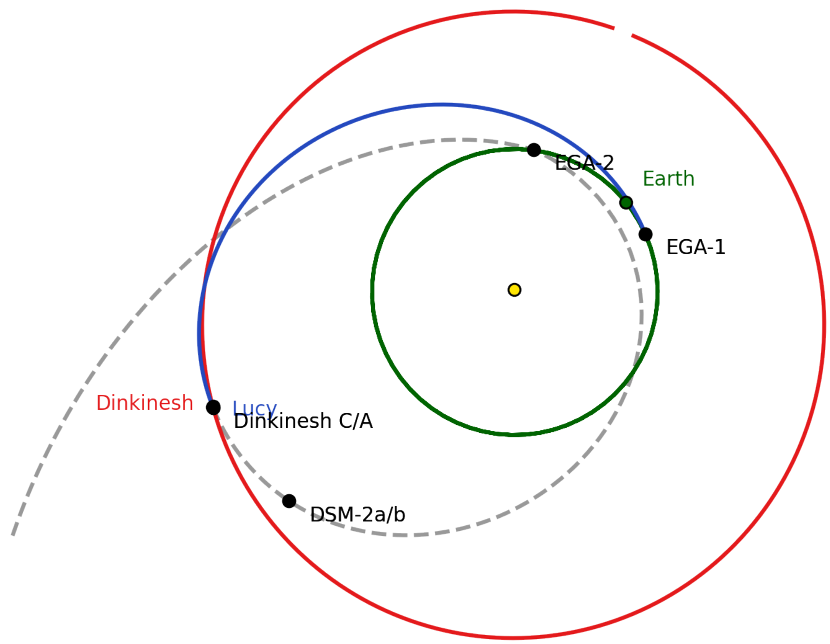


Figure 1: Trajectory of Lucy and Dinkinesh on 1 November, 2023

The first maneuver targeting Dinkinesh was Trajectory Correction Maneuver 08a (TCM08a) on 9 May, 2023 with a commanded delta-v of 3.438 m/s. TCM08a executed near perfectly so that the TCM08b clean-up maneuver computed to be 5.7 mm/s and slated for 20 June, 2023 was canceled.[2] The Dinkinesh encounter operations started 60 days out from the encounter on 2 September. The major milestones are shown in Figure 2. The purple, blue, and orange rectangles denote the radio and optical navigation tracking cadence. The magenta pentagons are the data cutoffs (DCOs) associated with either the maneuver final design deadlines or the final knowledge update (FKU). Finally, the green pentagons are the maneuver execution days or other critical events like the FKU upload to the spacecraft. The lower transparency boxes denote the nominal pre-encounter schedule, whereas the full color boxes are associated with the actual executed events timeline.

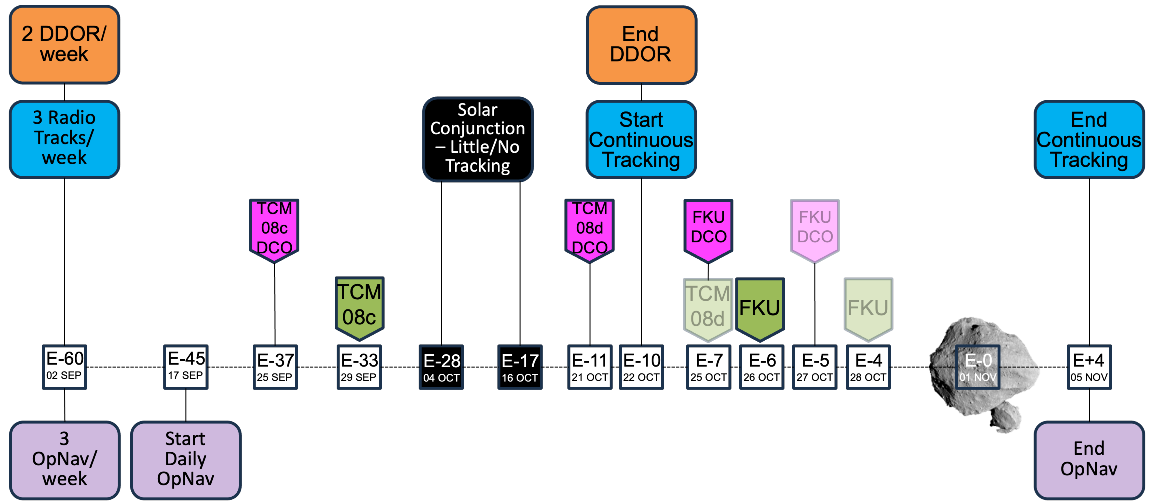


Figure 2: Nominal and Actual Dinkinesh Encounter Timeline

There were two major OD challenges associated with solar conjunction where the Sun-Earth-Probe (SEP) angle was 3 degrees or below for 13 days (4 October to 16 October). First, the TCM08c maneuver executed on 29 September, 2023 and the reconstruct had less than a week of degraded tracking due to the nature of the solar conjunction. During that time the Lucy velocity vector was orthogonal to the Earth Line of Sight (LOS), when the TCM08c reconstruct and subsequent predict was meant to bridge the nearly 2-week solar conjunction. Second, upon exiting the solar conjunction, the OD team immediately entered the TCM08d design cycle, with the preliminary design having only 2 days of tracking included, and the final design a total of 5 days of tracking.

Due to the significant efforts put forth by the OD team to model the forces acting upon the spacecraft as accurately as possible, the spacecraft trajectory prediction was stable with minimal drift, less than 0.13 mm/s and 80 m over the solar conjunction time span. This made the short maneuver design cycle with limited tracking possible. Additionally, the TCM08c maneuver was executed accurately, which also helped contribute to the cancellation of the TMC08d maneuver.

This maneuver design cycle was then followed up by the FKU decision point. The FKU is to provide the most up to date state information to the spacecraft from which to initialize the terminal tracking filter. For more information on terminal tracking, reference Kennedy et al. (2024). Figure 3 illustrates the various B-plane ellipses used in order to come to a decision, for the moment ignore the blue OD050 reconstruct information. The black ellipse $\mathbf{K}$ is the region of allowable knowledge error which is derived from the pre-encounter covariance analysis (discussed in the following section) which represents the ensemble of knowledge errors that could have been hypothetically possible to have been realized at the time the encounter sequence was designed. The $\mathbf{K}$ ellipse is centered on the 'current' on-board ephemeris at the time of the FKU decision. The green ellipse $\mathbf{F}$ is the FKU confidence region, in this example this is OD048 with its associated covariance. The Go/No-Go criterion for the FKU upload is contingent upon the FKU confidence region $\mathbf{F}$ being wholly contained within the region of allowable knowledge error $\mathbf{K}$ in both the B-plane and the TOF. If it is fully contained, then no FKU upload is required, but otherwise an upload will be performed. In the FKU decision meeting, based on the criterion, an FKU for the Dinkinesh flyby would not be performed. However, because this flyby was meant as an engineering check-out, the FKU had already been decided to be executed regardless of the actual criterion being met or not.

In Figure 3 the OD050 reconstruct was added after the fact to show that the pre-encounter covariance analysis, from which $\mathbf{K}$ was derived, was in-fact an accurate representation of the realized trajectory. Furthermore

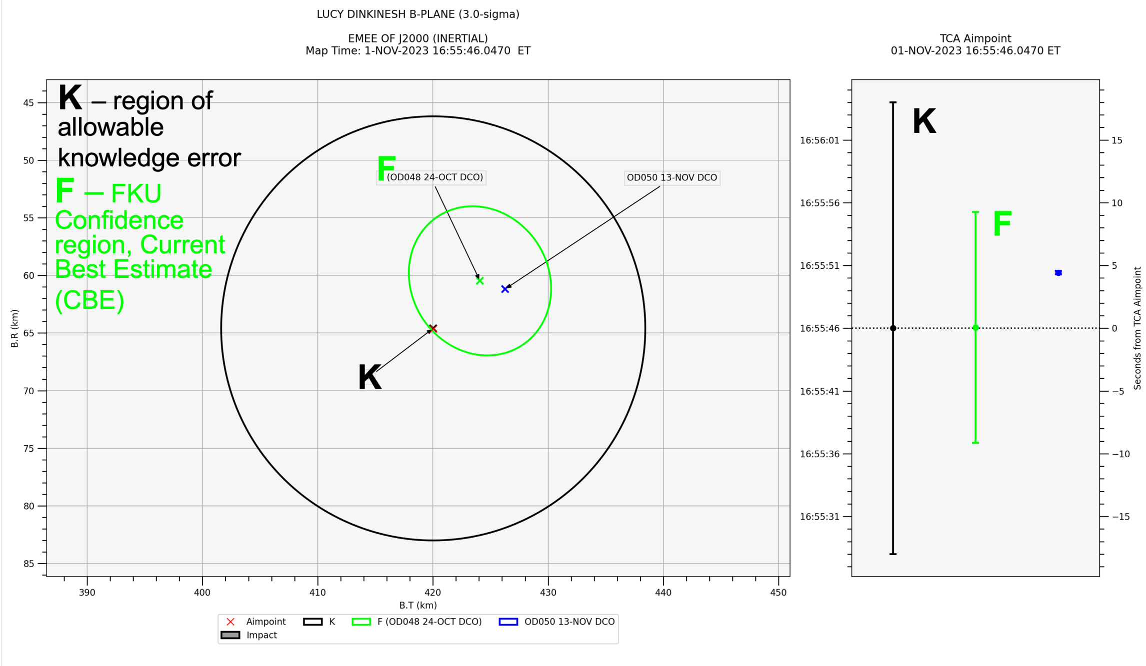


Figure 3: FKU Decision Criterion

the OD048 covariance also accurately captured the true flyby point in the B-plane. A primary objective of the engineering checkout of this flyby was to test the terminal tracking system that was previously mentioned, and it performed exceedingly well. It was able to capture and lock on the primary target, Dinkinesh, while also having a bright secondary object - Selam, in the camera's field of view. There was no preparation during this encounter to handle a binary system like the one observed, one could consider this a stressing scenario for an engineering test, which has provided some confidence in the spacecraft and the Lucy team's abilities. For another four days following the flyby we continued to receive continuous tracking as well as OpNavs. Afterward, the spacecraft returned to a cruise state with only radio tracking scheduled for once per week. The next section provides a quick overview of the covariance analysis which provided the basis and expectations of the OD performance leading up to the flyby.

Covariance Analysis

A year prior to the Dinkinesh flyby, when this asteroid encounter first came up as a possibility, a covariance analysis was performed to determine the state uncertainties and science feasibility. At the time of the analysis the nominal flyby altitude had not yet been decided but several values including 400 km, as well as a 3-σ low of 350 km were evaluated. Figure 4 illustrates the B-plane ellipsoid evolution given the DCOs on the abscissa. Note that in the figure, the final DCO is at the original FKU DCO of E-5 days, from then on it shows the predicted uncertainties. Furthermore, these are 'current' state uncertainties rather than smoothed. The uncertainty does not significantly come down until the first OpNav measurement is taken on 3 September. Then there is a steady decrease in the major and minor axes until the TCM08c maneuver is performed and the state uncertainty increases with the maneuver execution error. Within a few days of daily tracking and opnavs the TCM08c maneuver errors are expected to be solved for and back on track. The covariance analysis had tracking during solar conjunction, however it was significantly de-weighted based on Iess et al. (2012) for low SEP angles using empirical plasma noise models. This is different from what was flown since there was little to no tracking during the solar conjunction, this did not significantly affect the conservatism of the analysis as other factors were used to ensure the conservatism as well.

The covariance analysis used simulated radio data using the nominal tracking schedule that was expected

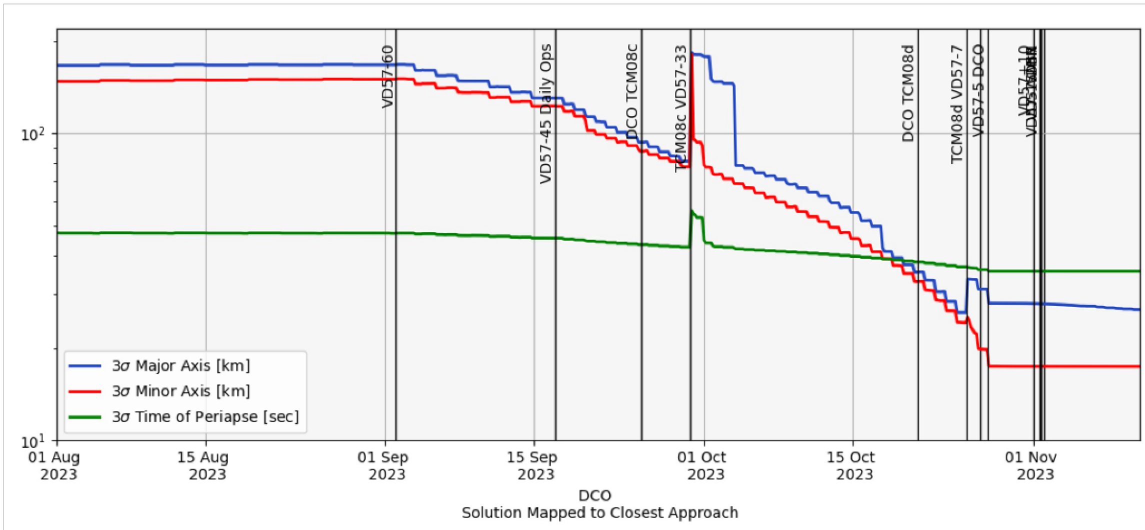


Figure 4: B-plane Ellipsoid Mapped to Close Approach for all Data Cut-offs.

to be requested from the Deep Space Network (DSN). For opnavs, one observable per epoch was simulated rather than an arbitrary larger number in order to have some conservatism to account for unknown factors such as brightness of the asteroid in the images. Comparing the covariance analysis uncertainties to what was flown we found that the covariance analysis was conservative in all three components of the B-plane, as expected, since the covariance analysis is meant to encapsulate the possible trajectories. The actual TOF uncertainty was on the same order of magnitude however, whereas the major and minor axes of the B-plane ellipse were an order of magnitude better (smaller) than what was predicted in the covariance analysis.

ORBIT DETERMINATION STRATEGY AND SETUP

The cruise OD strategy was presented in Geeraert et al. (2023), and some minor changes were made to adjust the setup for encounter operations. Those changes included estimating the Dinkinesh ephemeris SETIII parameters,[3] considering the GM, reducing the a-priori solar radiation pressure (SRP) scale factor by 1%, while also removing the stochastic component of SRP, and adding an estimated frequency bias for 3-way Doppler. Table 1 lists all the parameters for the encounter setup. The right ascension (RA) and declination (DEC) of the finite burns are defined in the in the Earth Mean Equator at Epoch (EMEE) J2000 frame. The Jet Propulsion Laboratory (JPL) Development Ephemeris 430 (DE430) ephemeris has been used up to this point in the mission but will likely be updated to DE440 in the Spring of 2024 because many of the future encounter asteroids' ephemerides are referenced to DE441.

The OD tools used for the Lucy mission is the Double Precision Orbit Determination Program (DPODP) also known as Mirage and is based on the pseudo-epoch state filter algorithms developed by Bierman (1977, republished by Dover in 2006).

The encounter utilized 2-way and 3-way Doppler, sequential two-way ranging (SRA), Delta Differential One-way Ranging (DDOR), and Lucy Long Range Reconnaissance Imager (L'LORRI) opnavs, the Terminal Tracking Camera[4] (TTCAM) images were not used in the OD other than for the initial OD (IOD) solution of Selam. The 2-way and 3-way Doppler plus SRA were weighted at three times the noise of the pass.[5] The DDORs, which are nominally weighted at 0.06ns, were weighted between 0.06 to 0.2ns depending on the SEP angle. The OpNavs were initially weighted at 0.5px prior to 5 October and subsequently were weighted

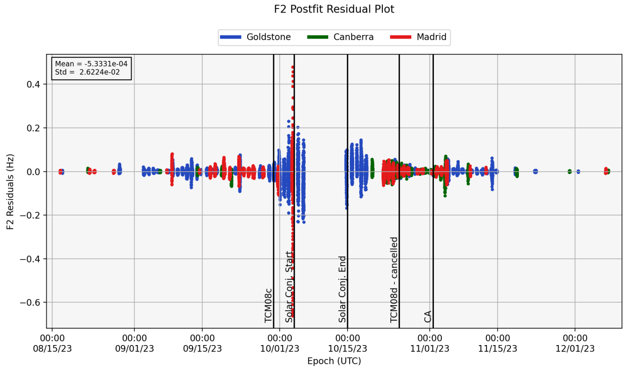
Table 1: Encounter Orbit Determination Filter Configuration

Parameter	Type	A-priori 1-σ	Notes
Epoch State	Estimated	3× previous arc sigma	State and uncertainty derived from previous arc
SRP Scale Factor	Estimated	0.02	-
Dinkinesh Ephemeris	Estimated	Correlated Covariance	SETIII parameters, correlated covariance from SSD
Finite Burns (ΔV, RA, DEC)	Estimated	30 mm/s + 4% of $\|\Delta v\|$	TCM thrusters only $<$10 m/s
Desats	Estimated	0.4 mm/s	Per axis
Per-Pass Range Biases	Estimated	4 m	White noise stochastic model, batch start at range pass
Per-Pass 3-way Frequency Biases	Estimated	0.1 Hz	White noise stochastic model, batch start at 3-way Doppler pass
Accelerations	Estimated	1.0E-12 km/s^2	Per axis, white noise stochastic model with 3 day batches
Accelerations $\pm$ 30 min to CA	Estimated	1.0E-12 km/s^2	Per axis, colored noise stochastic model with 10 min batches
GM of Dinkinesh System	Considered	4.665E-9 km^3/s^2	10% of the GM value
Future Desats	Considered	0.4 mm/s	Per axis
Future Accelerations	Considered	3.0E-12 km/s^2	Per axis, white noise stochastic model with 3 day batches
Earth Ephemeris	Considered	12×12 DE430 Earth-Venus Covariance	SET III parameters
DSN Station Locations	Considered	Correlated Covariance	Full Covariance for all stations except DSS-56
Troposphere	Considered	0.01 m / 0.01 m	Dry/Wet
Ionosphere	Considered	0.55 m / 0.15 m	Day/Night for X-band
Pole X and Y	Considered	0.002 m	-
UT1	Considered	0.025 m	-

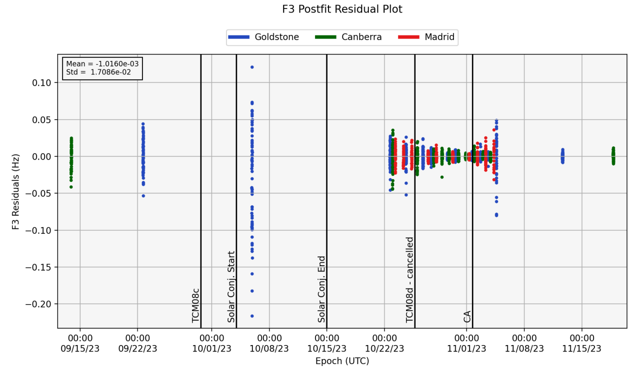
at 0.1px plus 20% the diameter of the small-body in pixel space. The close-approach OpNavs were further de-weighted once the Dinkinesh system was observed to be a binary because there now was a barycenter offset from the Dinkinesh center of figure. Figure 5 shows the radio-metric tracking data around the encounter in sub-figures (a)-(d). Sub-figure (e) shows all of the OpNav data with the largest residuals being approximately $\pm$ 10 pixels at close approach (CA) when the ground sample distance (GSD) was 2 m per pixel. Finally the last sub-figure (f) is a zoomed in plot on the OpNav residuals showing both the pixel and line components throughout the approach phase of the encounter.

Prior to any OpNavs for the Dinkinesh encounter, the radio data weighting was varied and then combined with all the various combinations of other radio data types and weightings. When performing these trades and plotting the resulting B-planes, we found that the solutions were all consistent with minimal variations compared to the size of the covariances. This demonstrated that the different measurements were independently producing consistent OD solutions, which provided some confidence in the solution as we were approaching the asteroid.

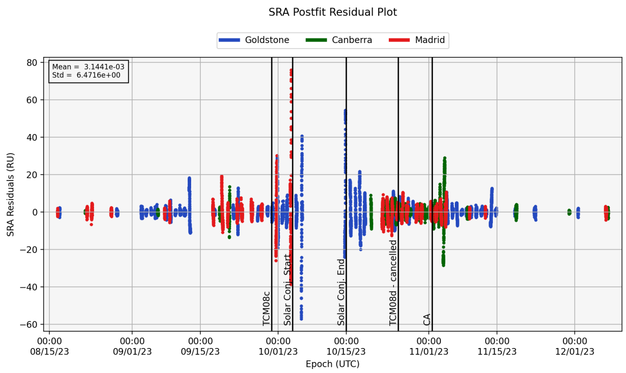
Near-daily OD solutions were generated to track Lucy's progress, and nine of those solutions (OD041 to OD050) were official ODs which were delivered within the encounter timeline from Figure 2. The following section covers the solution history of those OD solutions as well as how they compared to the delivery ellipse, which was used by the Science Operations Center (SOC) in designing their science sequences.



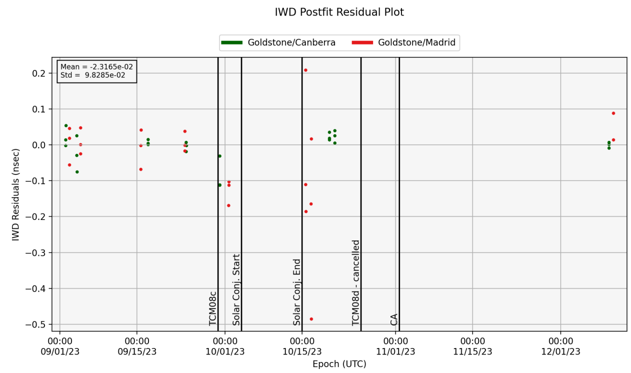
(a) Two-Way Doppler (17.75 mm/s per Hz)



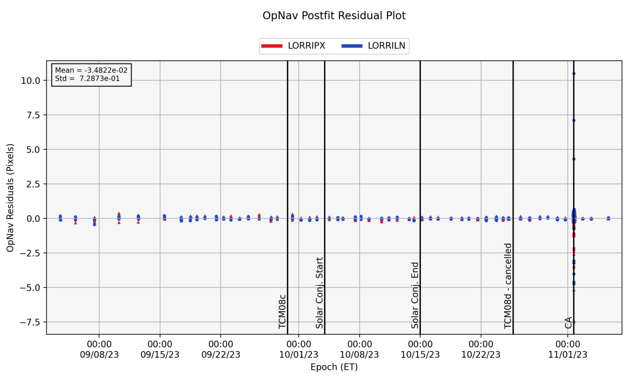
(b) Three-Way Doppler (17.75 mm/s per Hz)



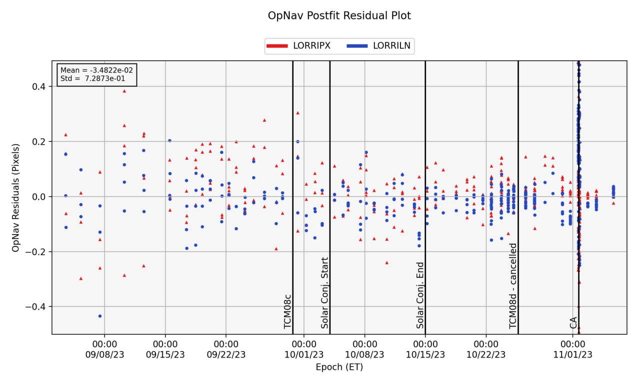
(c) Sequential Two-Way Ranging (7076 RU/km)



(d) ΔDOR



(e) LORRI Pixel and Line



(f) LORRI Pixel and Line Zoom

Figure 5: Radio-Metric and OpNav Tracking Residuals from OD050

ORBIT DETERMINATION SOLUTIONS DURING OPERATIONS

The first OD during the encounter phase was OD041, with a radio data cutoff (DCO) of 6 September and did not include any OpNavs. The subsequent OD was OD042 which had a DCO of 14 September and included the first set of OpNavs. OpNav processed L'LORRI 1×1 images from three separate epochs E-59, E-57, and E-55 days, for a total of 216 images. Dinkinesh was significantly dimmer than expected, motivating an increased number of images of 24 in each coadd, yielding three observables per epoch, resulting in nine observables total for OD042. The passthru of the OpNavs was a first look at how close Dinkinesh was to the a-priori ephemeris. The residuals only had a spread of ± 0.3 px, even though Lucy was still more than 21 million km away, this was an encouraging first glimpse.

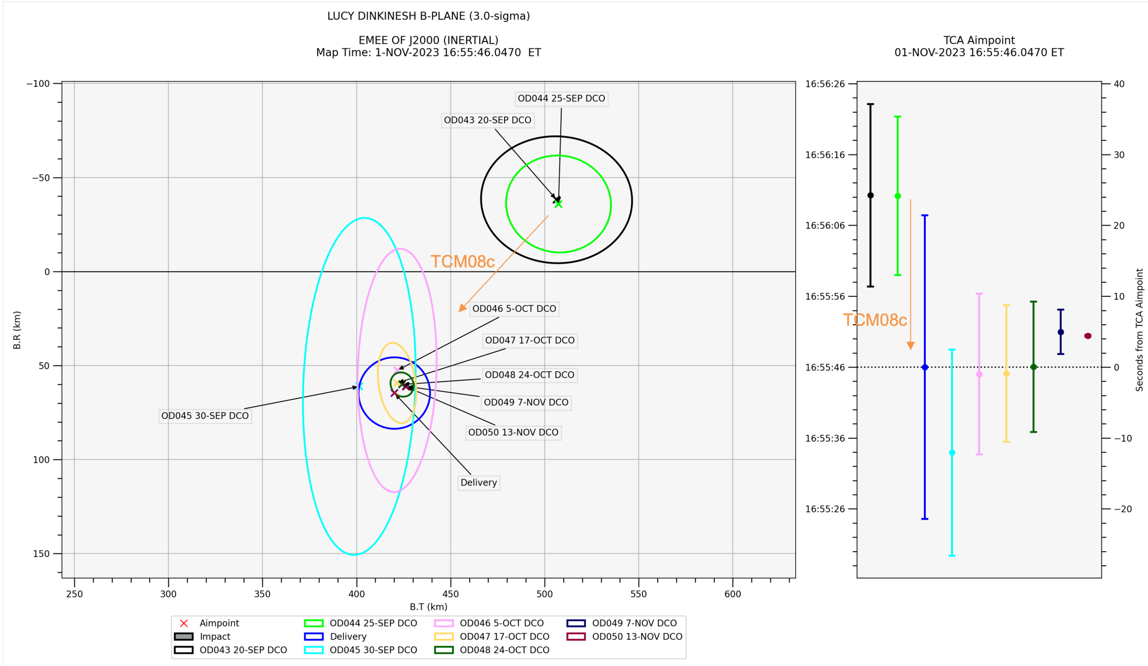


Figure 6: B-plane Progression OD043 - OD050

Figure 6 shows the delivered OD solution history mapped to the Dinkinesh B-plane in the EMEE J2000 frame starting from OD043 past the close approach to OD049 and OD050 which presented the preliminary reconstructs of the flyby. Each of these ODs included the daily OpNav observables and has the DCO listed in the label. OD043 and OD044 shows a stable OD solution with limited movement of Dinkinesh in the estimated ephemeris. This location in the B-plane was the runout from the first Dinkinesh targeting maneuver TCM08a executed on 9 May, with its aimpoint being the red × located at 420.057 km in B·T, 64.630 km in B·R, and a time of flight (TOF) of 1 November, 2023 16:54:36.864 UTC (1 November, 2023 16:55:46.047 TDB). The difference between the aimpoint and the OD044 B-plane solution was primarily due to the TCM08a execution error propagated from May to November, with a small contribution in OD predict error over that same time.

TCM08c used OD044, with a DCO of 25 September, for the final design of the maneuver which executed on 29 September. OD045 in Figure 6 shows the preliminary reconstruct of the TCM08c with only 1.5 tracks of Doppler and SRA. That initial reconstruct was out of family with the subsequent ODs and is due to the limited and degraded (due to the solar conjunction) tracking used, as well as the poor geometry where the spacecraft velocity direction was nearly perpendicular to the Earth LOS. The subsequent ODs from OD046 through OD050 were stable and consistent. The blue delivery ellipse is 19 km in radius and is 21.4 s 3-σ in TOF, these values were obtained from a covariance and monte carlo analysis prior to the encounter. It is important to note that the covariance analysis used the nominal operations schedule, and also assumed all the maneuvers are executed. Therefore the delivery ellipse is effectively the expected dispersions and knowledge following TCM08d. These navigation uncertainties were delivered to the SOC to which the science team designed the encounter sequence. With OD048 we were at 99.$\bar{9}$% of being inside the delivery ellipse and as a result the TCM08d maneuver was canceled. Had we executed TCM08d to attempt to center the state on the aimpoint, the maneuver execution errors would be significantly larger than the current knowledge errors and there would be a possibility that we would be farther from the aimpoint then our current solution.

The TOF uncertainties shown in Figure 6 stayed large, almost ±10 s, until the actual close approach occurred. This is because the OpNavs did not provide any TOF information until some parallax was observed which was only within the several hours surrounding the close approach. The post flyby ODs of OD049 and OD050 indicated that we arrived at the close approach point late compared to the aimpoint. This delay corresponds to a lag in the transverse location of Dinkinesh which is discussed further in the Dinkinesh trajectory reconstruct section. The preliminary values obtained during the reconstruct are also presented in a subsequent section.

Probability of the Current State and Covariance being inside the Delivery Ellipsoid

During operations, as the spacecraft approached the close encounter date the current OD solution with its covariance tended to decrease as more data is incorporated. However, while we expect to be inside the delivery ellipse and TOF uncertainty at the time of the last maneuver, that may not be the case prior to that time. An example of this is all the ODs prior to OD048 which have uncertainties larger than the delivery ellipse. In those cases it may still be beneficial to evaluate the probability of being inside the delivery ellipse given the OD's covariance. For example for OD047, the probability of being inside the delivery ellipse was 96.5%, making it likely that the final maneuver TCM08d would be cancelled. The process for computing this probability was by creating a large monte carlo sample based on the 3-D position covariance, then determining how many of those points are inside and outside of the delivery volume. This method quickly approximates the triple integral over the probability density function, and is easier to evaluate and update for future use.

Error Budget Analysis

The yellow OD047 and blue delivery ellipse from Figure 6 are shown as the green and black ellipses in Figure 7. Many smaller ellipses are shown inside the OD047 ellipse which represent the individual parameter uncertainty contributions of the OD047 B-plane ellipse. An error budget like this one helps the OD analyst understand where the uncertainty is coming from, and possible ways of reducing that uncertainty.

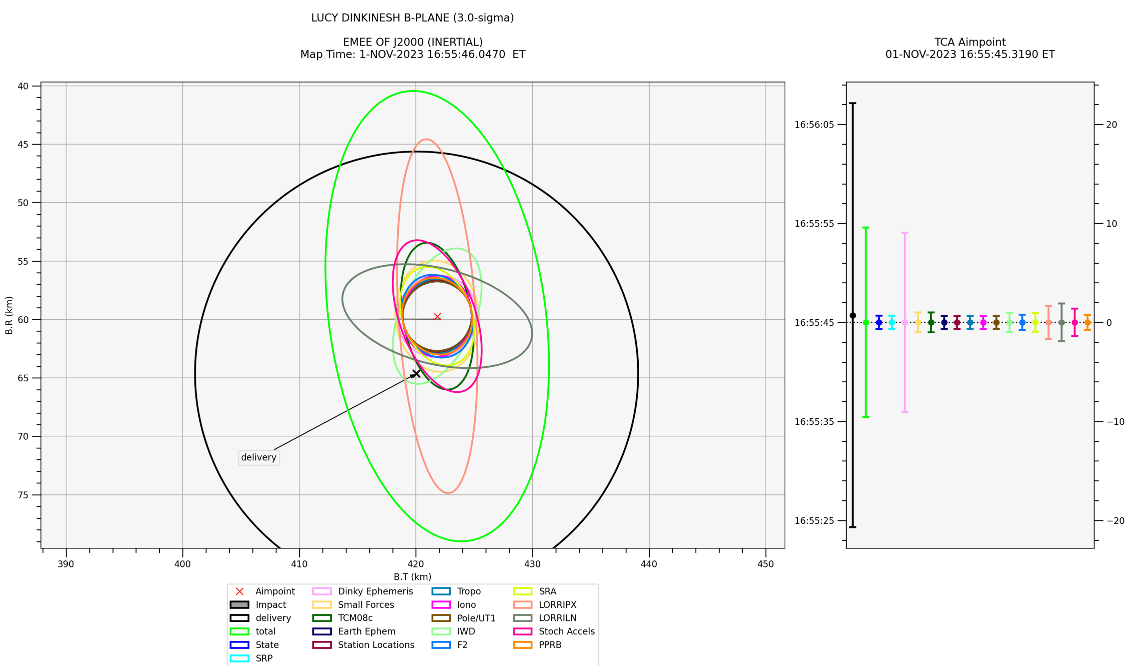


Figure 7: OD047 B-plane Error Budget

The largest uncertainty contribution in the B·R axis is the L'LORRI pixel coordinate (LORRIPX) measurement sigma of 0.5 px, whereas the largest uncertainty in the B·T axis is the L'LORRI line coordinate

(LORRILN) measurement sigma, also of 0.5 px. This means that by tightening the L'LORRI opnav measurement weighting, this will most significantly reduce the OD047 B-plane ellipse. Whether or not that is appropriate is a different question, and also depends on the opnav residual spread. The uncertainty in the Dinkinesh ephemeris is by far the largest contribution of uncertainty in the TOF direction, this insight illustrates the the TOF uncertainty will remain high until the actual flyby occurs and the geometry between Dinkinesh and Lucy changes rapidly.

LUCY TRAJECTORY RECONSTRUCTION

In this section we present the preliminary Lucy trajectory reconstruction during the flyby based on OD050 which had a DCO of 13 November, 2023. All the radio-metric and OpNav data shown in Figure 5 were utilized in this reconstruct OD solution. The following is a summary of close approach by the numbers:

- Time of close approach of Dinkinesh

  1-NOV-2023 16:55:50.47 TDB $\pm$ 0.05 s 1σ

  1-NOV-2023 16:54:41.29 UTC $\pm$ 0.05 s 1σ

  4.42 s later than targeted by TCM08c

- Radial distance to Dinkinesh

  430.63 $\pm$ 0.02 km 1σ

  5.63 km farther from Dinkinesh than targeted by TCM08c

- B-plane parameters in EMEE

  426.26 $\pm$ 0.02 km 1σ B·T

  61.20 $\pm$ 0.02 km 1σ B·R

  7.08 km from TCM08c B-plane target

- Flyby speed

  4.491 $\pm 5 \times 10^{-7}$ km/s 1σ

Note that the sigmas provided above are the formal uncertainties from the filter. These uncertainties have the following assumptions in the filter setup. The Dinkinesh-Selam system mass is set to 6.99×10^{11} kg which is within the approximated system mass range mentioned in section "Initial Orbit Determination of Selam" on page 13, and the GM was only considered rather than estimated because the acceleration was below the stochastic threshold of 1E-12 km/s^2. Another assumption is that the OpNav centering was based on a sphere rather than a shape model, future reconstructions will indeed implement the center-finding algorithm using the Dinkinesh shape model, but that was not yet the case for OD050. Next, there was no distinction made between the Dinkinesh system barycenter and Dinkinesh itself which we have computed to be on the order of 100 m.

During the cruise phase as well as the early stages of the encounter phase the stochastic accelerations estimated on the spacecraft were small, well under 1E-12 km/s^2. However, during the close approach of the Dinkinesh system flyby, we noticed that larger stochastic accelerations were estimated, up to 2E-12 km/s^2. The standard cadence for the encounter phase stochastic batches is once every 3 days, but these were brought down to 10 min batches with a 30 min correlation time for 30 min before and after the nominal close approach time. There are several possible explanations for the modeling discrepancies compared to reality. First, in order to track the asteroid Lucy does a pitch-back maneuver where the spacecraft turns 180° compared to Earth-point (or Sun point since the low SEP), this means that the back of the solar arrays are now facing the Sun. This is the first time the spacecraft has been in this attitude, and there is likely some mis-modeling of the optical values associated with the back of the arrays. Second, the IPP movement is not modeled on the OD side, any attitude change from the stowed position would result in a deviation. The noisy-ness seen on the spacecraft could be attributed to this movement.

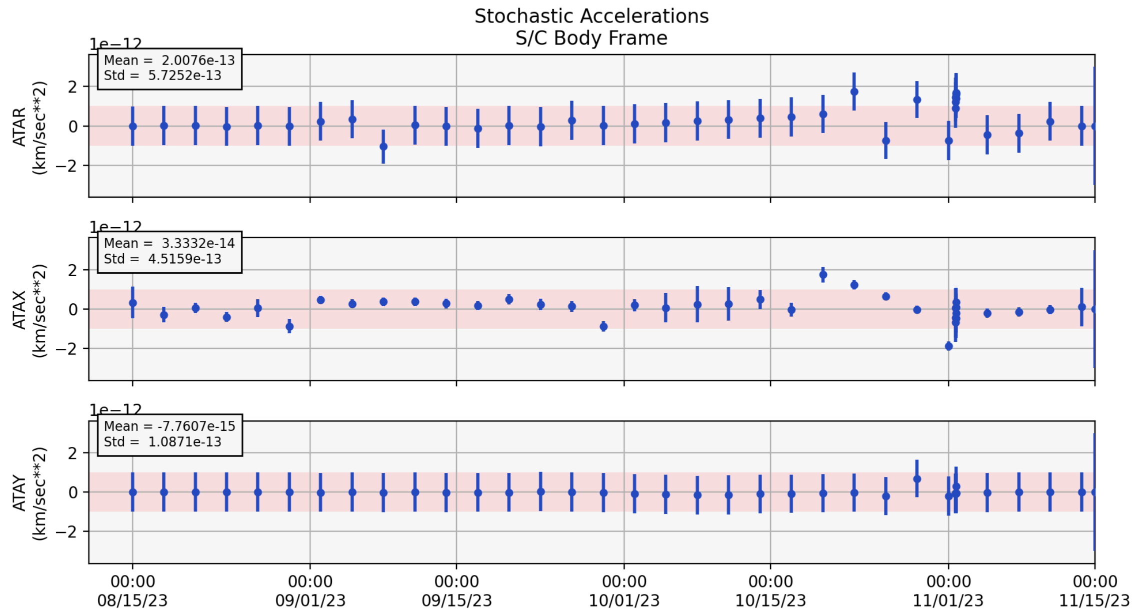


Figure 8: Stochastic Accelerations During the Encounter Phase

TCM08c was the only maneuver executed during the encounter phase. Table 2 lists the reconstruction of TCM08a as well, for completeness and continuity with the Geeraert et al. (2023) paper. Notice that the smoothed sigma on the TCM08c declination is still large, and subsequent tracking data is no longer bringing that uncertainty down. The primary reason for this is the observability of the maneuver and the geometry of the spacecraft with respect to Earth. Since the spacecraft velocity vector is mostly orthogonal to the Earth LOS, there is little direct measurement information from Doppler or Range, however several ΔDOR measurements could provide the needed plane-of-sky information. When looking at the error budget in Figure 7, we see that the TCM08c maneuver uncertainty is primarily elongated in the B·R direction which corresponds with the declination direction of the maneuver. Then, observe that the ΔDOR (IWD on the plot) uncertainty is also primarily along the same direction, and a reason for the larger uncertainty still found in the declination of the TCM08c maneuver.

Table 2: Executed Maneuver Reconstructions

Maneuver	**Epoch (UTC)**	**Parameter**	**Design**	**Estimated**	**Smoothed σ**	**A-priori σ**
TCM-08a	9-May-2023 17:00:00	ΔV (m/s)	3.4384	3.4410	0.001955	0.02387
		RA (deg)	22.4974	22.2329	0.02259	0.9048
		DEC (deg)	-26.1690	-26.04176	0.05967	0.8120
TCM-08c	29-Sep-2023 17:00:00	ΔV (m/s)	0.0608	0.0619	0.001236	0.006678
		RA (deg)	111.0903	111.06726	0.2354	8.9966
		DEC (deg)	-9.0622	-7.9047	1.4475	8.8843

The following section presents the reconstruction of the Dinkinesh trajectory as well as an initial IOD state for Selam. The orbit determination of Selam is still on-going and will be subject to a future paper.

DINKINESH AND SELAM TRAJECTORY RECONSTRUCTION

Dinkinesh Trajectory Reconstruction

When the Dinkinish encounter was added to the Lucy timeline in early 2023, the navigation team received a Dinkinesh ephemeris, covariance, and partials files from the JPL Solar System Dynamics (SSD) group. That ephemeris was used for the covariance analysis. However, additional astrometry of Dinkinesh from observations between November 2022 and February 2023 were submitted to the Minor Planet Center (MPC), the results of the observation campaign were presented in Mottola et al. (2023). SSD updated the Dinkinesh ephemeris and associated files which were delivered to the navigation team in March of 2023 to be used for the encounter and as the a-priori current best estimate of the Dinkinesh ephemeris. We knew from the covariance analysis that upon approach we would have almost no observability in the spacecraft velocity ($\mathbf{v}$) direction of the Dinkinesh ephemeris until we were much closer and able to observe some parallax. However, we also knew that we were expecting to get good estimates of the angular momentum ($\mathbf{H}$) and $\mathbf{v} \times \mathbf{H}$ directions. As a result, throughout the approach phase the TOF uncertainty which corresponds to the velocity direction remained high and only minimally decreased with additional OpNavs. During the close approach phase where the spacecraft-asteroid geometry evolved rapidly, the TOF uncertainty pinched down significantly allowing us to estimate a more accurate location of Dinkinesh in its heliocentric orbit.

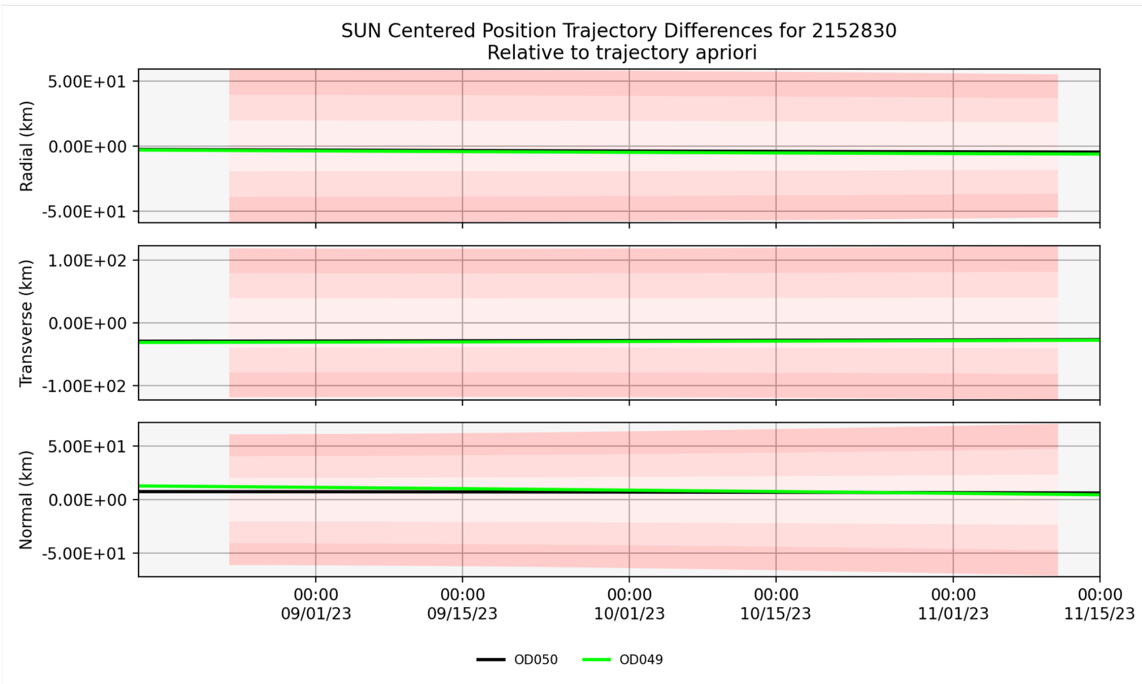


Figure 9: Estimated Dinkinesh Ephemeris Compared to the Apriori Ephemeris

Figure 9 illustrates the a-priori Dinkinesh ephemeris as the baseline 0.0 km centers in RTN. Around that baseline is the a-priori ephemeris uncertainty with 1, 2, and 3σ bounds in increasing darker shades of pink. The OD049 and OD050 Dinkinesh estimates are shown relative to the a-priori ephemeris. Recall that the difference between OD049 and OD050 is that OD049 is only using the un-resolved OpNavs whereas OD050 is using all the un-resolved images plus resolved OpNavs near close approach as well. Both solutions suggest that the a-priori ephemeris was accurate with an appropriately scaled covariance, the new ephemeris estimate is within 1-σ Sun-centered RTN. The largest change in the ephemeris was estimated in the Transverse direction, lagging slightly behind were we initially expected Dinkinesh to be. This lagging corresponds with the 4.42 second delay of the close approach time as well.

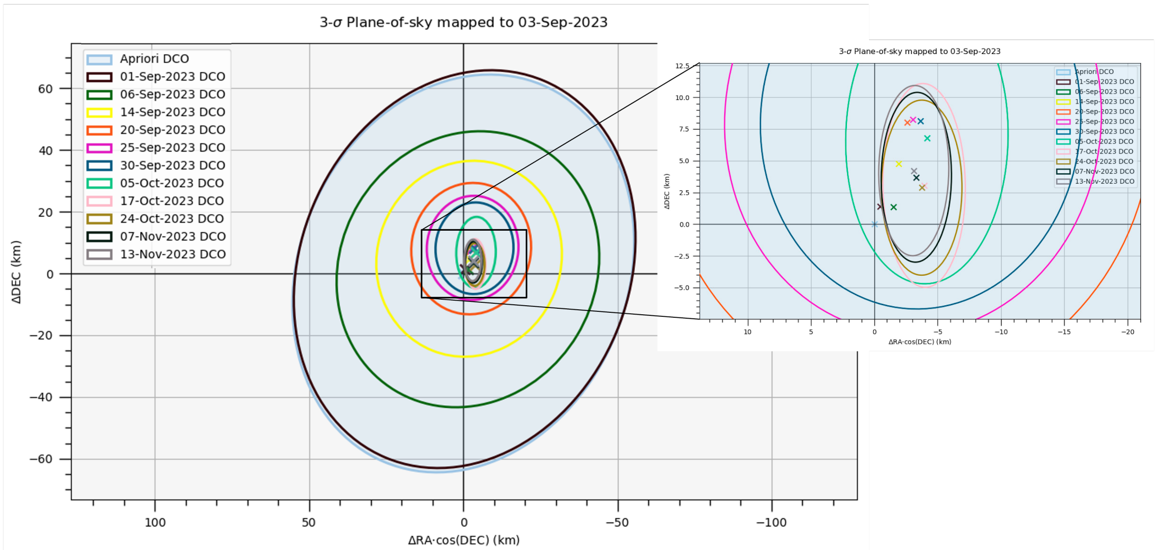


Figure 10: Dinkinesh Ephemeris and Covariance in Plane-of-Sky Mapped to First OpNav Epoch

Finally in Table 3 we summarize the a-priori values of the Dinkinesh ephemeris and the estimated values in our filter using the unresolved plus resolved images of Dinkinesh. The osculating elements are mapped to the 13 September, 2023 TDB epoch as those are the elements listed on JPL's small-body database. The elements are as follows: e is the eccentricity, a is the semi-major axis, i is the inclination, Ω is the longitude of the ascending node, ω is the argument of periapsis, and lastly t_p is the time of periapse passage. The final formal 1-σ uncertainties are included as well and all have slight reductions in their uncertainty compared to the a-priori. All values shifted less than 1/3-σ compared to the a-priori uncertainty.

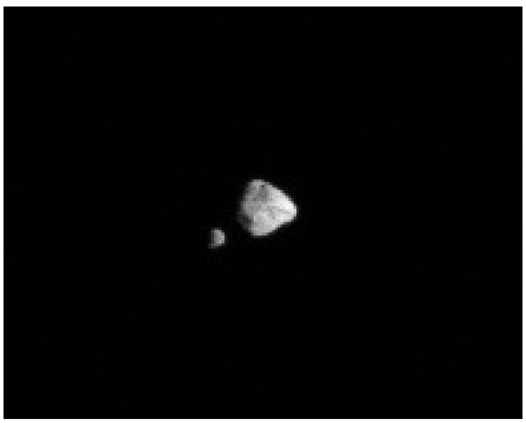
Table 3: Dinkinesh Osculating Elements Mapped to 13-Sep-2023 00:00:00.00 TDB

element	A-priori Value	A-priori 1-σ	Estimated Value	1-σ
e	0.1121065510519112	3.3613E-8	0.1121065**573726**	3.3388E-8
a [AU]	2.191542650193643	6.8432E-9	2.19154265**23108157**	5.0078E-9
i [deg]	2.093589035443616	2.1525E-6	2.093589**3**	1.4936E-6
Ω [deg]	21.38225834685511	9.0626E-5	21.3822**740**	1.0283E-5
ω [deg]	66.76552723703738	9.3606E-5	66.7655**071**	7.7680E-6
t_p [TDB]	2459917.595401357656	6.1734E-5	2459917.595**3856003**	1.0283E-5

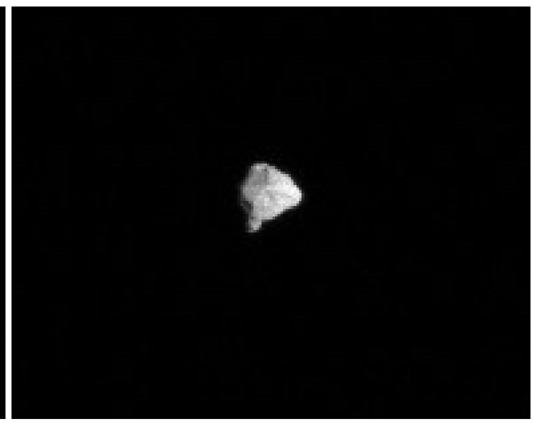
The following section goes through the process of computing an initial state for Selam. At this point, only the state is provided rather than a full OD solution of Selam orbiting Dinkinesh as that is still an on-going analysis.

Initial Orbit Determination of Selam

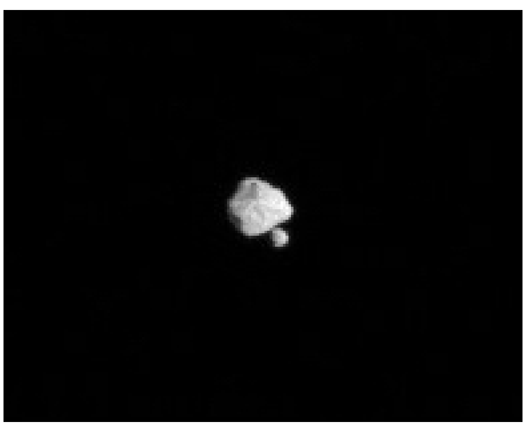
The very first images that were sent back from the Lucy spacecraft during the flyby are shown in Figure 11, these were taken with TTCAM . This camera has a wide FOV of 11° by 8.2°, which from the Lucy flyby distance of 430 km results in a small but resolved image of Dinkinesh and Selam. The four images in Figure 11 are significantly cropped as a result. These four .fit images were loaded into the SAOImageDS9 software package[6] and the centers of each body were manually recorded in pixel space, along with the time associated with each image embedded in the header of each file. The OD team assumed that the amount of orbital movement from Selam around Dinkinesh in the 40 second span of the images was negligible and well within the noise and therefore would be a suitable first order approximation. Using the OD048 predicted SPK for Lucy and Dinkinesh, as well as the predicted spacecraft and IPP attitude files covering 18 October, 2023 to 15 November, 2023 the OD team computed a preliminary value for the Dinkinesh-Selam separation of 3.3 km. The OD script, written to triangulate the Selam position relative to Dinkinesh, looks at the vector from the Lucy TTCAM boresight to the observed center of both Dinkinesh and Selam for each image and assumes the spacecraft distance to Dinkinesh is accurate. From there a least-squares solution of the intersection of the four boresight vectors for Selam's location is computed. Figure 12 illustrates the four vectors, but for clarity they do not extend all the way out to the Lucy spacecraft in order to distinguish the primary and secondary bodies in the plot. Lucy appears to flyby Dinkinesh from left to right (approximately in the direction of the +Y J2000 inertial frame direction) because Dinkinesh's heliocentric velocity was greater than Lucy's and therefore overtook the spacecraft in its heliocentric orbit. As a result the red vector corresponds to Figure 11(a), green with Figure 11(b), yellow with Figure 11(c), and finally blue with Figure 11(d).



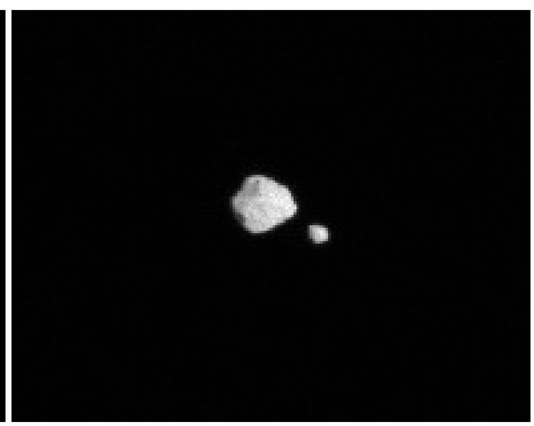
(a) 2023-11-01T16:54:13.584 UTC



(b) 2023-11-01T16:54:27.584 UTC



(c) 2023-11-01T16:54:40.584 UTC



(d) 2023-11-01T16:54:53.584 UTC

Figure 11: TTCAM Images During Close Approach

By November 3, the reconstructed spacecraft attitude had been downlinked and processed by NAIF. Using these updated files, the OD team solved for a preliminary reconstructed trajectory of the flyby using unresolved images from before and after the flyby this solution corresponded to OD049. Using OD049 and the reconstruct attitude files, along with the four same images from Figure 11 we updated the Dinkinesh-Selam separation to 3.2 km suggesting that the initial solution using only the predict files was not too far off. Note that when doing the manual center-finding on these TTCAM images of Selam we did not yet know that this object was in fact a contact binary and elongated in direction not visible in these images. That would result in an error of the estimated center of figure and by association the center of mass likely as well.

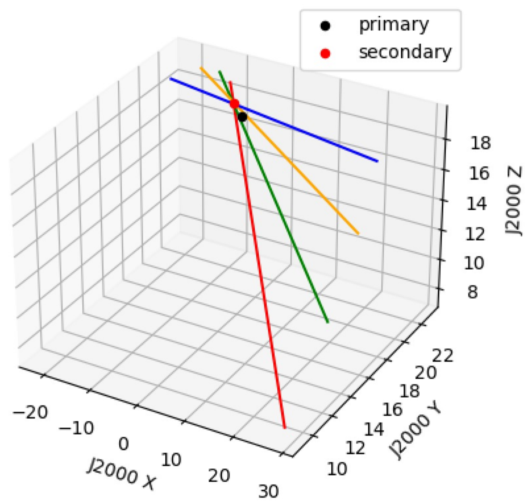


Figure 12: Selam IOD with Four Triangulated TTCAM Vectors

The preliminary estimate of position of Selam relative to Dinkinesh at the close approach time in the EMEE J2000 frame is $\begin{bmatrix}-3.13 & 0.72 & 0.25\end{bmatrix}$ km . Provided that the bulk density of an S-type asteroid is 2000-2500* kg/m^3 and the radius of Dinkinesh is estimated at 408 m and the radius of each of Selam's lobes is estimated at 110 m, then we have a system mass between 5.9×10^{11} and 7.4×10^{11} kg. From the Dinkinesh-Selam mass ratio we can infer that the barycenter is located approximately 122 m from the Dinkinesh center of mass along the Dinkinesh-Selam vector. Therefore the Selam location with respect to the barycenter at the close approach time would be $\begin{bmatrix}-3.01 & 0.70 & 0.24\end{bmatrix}$ km, also in the EMEE J2000 frame. Assuming a circular orbit, we can then compute the low and high system mass orbital speeds associated with the previously provided position vector. The low system mass orbital speed of Selam relative to the barycenter is 0.106 m/s whereas the high system mass corresponds to 0.119 m/s. Obtaining the velocity vector is not trivial though because an additional constraint on the orbital plane is required. For the IOD process we make the following assumption: the orbital plane of Selam could reasonably be within the plane of the equatorial ridge of Dinkinesh which is also approximately located within the orbital plane of Lucy. Using this assumption and an average density of 2250 kg/m^3 for both Dinkinesh and Selam we obtain the following velocity vector of Selam relative to the barycenter $\begin{bmatrix}1.73 \times 10^{-5} & 3.96 \times 10^{-5} & 1.04 \times 10^{-4}\end{bmatrix}$ km/s. This velocity vector results in a retrograde orbit, a prograde version should also be computed as that is another possibility. The Selam IOD state vector is the a-priori state with which to initialize the filter and attempt to estimate the Selam orbit, if it is indeed observable.

CONCLUSION

The OD performance throughout the Dinkinesh encounter phase exceeded the pre-encounter analysis. The Lucy team successfully flew by Dinkinesh and discovered a companion, a contact binary, now named Selam. The OD processes have been exercised and some lessons learned have been documented for future encounters. We have presented the preliminary reconstruct analysis that was done by the OD team immediately following the flyby for Lucy as well as Dinkinesh. A preliminary guess at the state for Selam has also been demonstrated. Over the upcoming months the OD team will continue working on estimating the Selam orbit

*The S-type density range in Carry et al. (2012) is 2000-3000 kg/m^3, however, the authors also mention that there is an increasing trend in density with mass, hence the lower density range used for a small binary system like Dinkinesh and Selam.

around Dinkinesh using the delivered opnavs. A preliminary shape model for Dinkinesh has also been delivered in the mean time, and those opnavs have been re-processed, and will be used in subsequent refined reconstruct ODs.

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