OPTICAL NAVIGATION AND ORBIT RECONSTRUCTION OF NASA'S LUCY FLYBY OF ASTEROID DINKINESH AND ITS MOON

Derek S. Nelson,[1*], Eric M. Sahr,[1] Joel Fischetti,[1] Jeroen L. Geeraert,[1] Erik Lessac-Chenen,[1], Coralie D Adam,[1], John Y. Pelgrift,[1], Dale Stanbridge,[1] Kevin Berry,[2] ; [1]Space Navigation and Flight Dynamics Practice, KinetX, Inc., 21 W. Easy Street Ste. 108, Simi Valley, CA 93065, [2] NASA/GSFC Navigation and Mission Design Branch, 8800 Greenbelt Rd, Greenbelt, MD 20771, USA. [*][derek.nelson@kinetx.com]

Abstract. *NASA's Lucy spacecraft performed a close flyby of asteroid Dinkinesh and its moon, Selam, on November 1, 2023, during which the on-board high-resolution L'LORRI imager captured a series of extended images of both bodies against a background starfield. These images were used to perform optical navigation (OpNav) of the Lucy spacecraft relative to the asteroids by computing the centers of figure of each asteroid in the image set. The inertial orientation of each image was determined using a variety of attitude determination techniques such as star centerfinding and attitude interpolation, and a combination of cross-correlation and moment centerfinding were used to compute the asteroid centers of figure. These astrometric results were then processed in an orbit determination filter to estimate the spacecraft and asteroid ephemerides during the flyby. The optical navigation processes and results as well as the orbit estimation results will be presented and analyzed.*

Introduction. Optical navigation is a critical function that can be used to precisely estimate the orbit of a spacecraft relative to an observed object, as well as the orbits of visible targets relative to their centers of motion. Extended images of Dinkinesh and its smaller moon, Selam, were captured during by the L'LORRI imager[1] on-board NASA's Lucy spacecraft flyby on November 1, 2023. These resolved images of Dinkinesh and Selam against a background starfield were used to reconstruct the trajectory of the Lucy spacecraft, Dinkinesh and Selam during the period of a few hours around closest approach. The optical navigation and orbit determination processes and results in support of this objective are discussed and analyzed.

Attitude Determination. L'LORRI images captured during the few hours around closest approach 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 done to both provide conservatism 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.[2] 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
2. Linear interpolation between two long-exposure stellar images
3. Delta-attitude computation using reconstructed spacecraft attitude telemetry (Delta-CK)[3]

These methods were used during different imaging phases, which are illustrated in Figure 2. These methods and how each was used to compute the short exposure image attitudes will be discussed in detail.

Asteroid Centerfinding. Determining the centers of figure of Dinkinesh and Selam involved several steps which sequentially improved the astrometric precision. First, Dinkinesh and Selam centers were computed using a cross correlation method with a spherical shape model as well as a moment centerfinding method, since a representative 3D shape model of each asteroid was not yet available. After the Lucy science team constructed the Dinkinesh 3D shape model, the optical navigation team used that model 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 Figure 1. The observed center determined by the cross-correlation, as well as the predicted Dinkinesh limb outline is also provided in Figure 1.

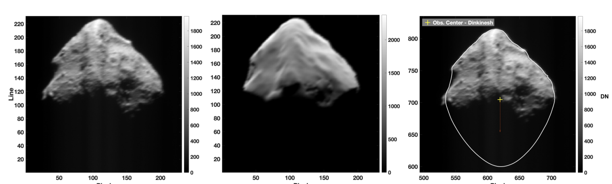

Figure 1. Left: Image of Dinkinesh as captured during closest-approach using the L'LORRI imager. Center: Corresponding simulated image of Dinkinesh using the 3D shape model of Dinkinesh and representative lighting. Right: Real image of Dinkinesh overlaid with the observed center of Dinkinesh as computed 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.

This cross correlation method allowed for precise determination of the Dinkinesh centers of figure in all resolved images of Dinkinesh. The same cross correlation process will be performed with Selam once the 3D shape model is constructed. Currently, the Selam centers of figure have been calculated using a moment algorithm that finds the moment center of thresholded lit pixels of the target. The center residuals for Dinkinesh and Selam relative to an intermediate (unfinished) orbit delivery for Lucy, Dinkinesh and Selam are presented in Figure 2.

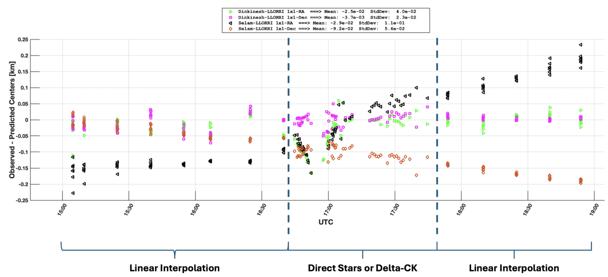

Figure 2. Dinkinesh and Selam center of figure residuals in units of km, with respect to an intermediate (unfinished) orbit solution for Lucy, Dinkinesh and Selam. The different phases of attitude determination during different image phases are identified.

Orbit Determination. Prior to the Dinkinesh flyby, there was no confirmed knowledge of this asteroid being a binary system. While the orbit determination (OD) of this flyby was previously discussed in Geeraert et al. (2024) it had limited information on the OD of the Selam orbit about Dinkinesh.[4] Furthermore, the Dinkinesh reconstruction did not utilize a shape model for the center finding algorithm. In this report, the final reconstruction is presented with the latest shape model and Selam information.

The period of L'LORRI OpNav imaging surrounding the closest approach to Dinkinesh, in which the bodies are resolved, is less than 8% of the observed orbital period and provides OD with a challenge in solving for the orbits of both Dinkinesh and Selam. A decent a-priori value of the position of Selam relative to Dinkinesh can be established through multiple OpNav images. However, the apriori velocity component is mostly a guess and based on several assumptions, one of which is that Selam is likely to be in a circular orbit.[5] These assumptions are applied in the form of a priori values, uncertainties, and ephemerides, with varying OD setups to represent a multitude of likely states.

To determine the robustness of the OD solution, a simulated setup with known parameters is prepared as a first step. Simulated OpNav images are used within the OD to analyze the satellite covariance and the effect on solution convergence when using imperfect a priori satellite ephemerides. With limited knowledge of the system resulting only from ground based and Lucy approach observations, the covariance is not fully constrained in all states. Once the simulated setup is understood and what estimated parameters are observable, this knowledge can be applied with some confidence to the actual OD of Selam about Dinkinesh to determine its orbit.

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