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Simulating Lucy's flybys of its target Trojan asteroids

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Abstract

Over its 12-year journey through the asteroid Main Belt and the L4 and L5 swarms of Jupiter Trojans, NASA's Lucy mission will visit a total of 9 asteroids across 6 encounters. Each one of these encounters is a flyby, which means that a given set of observations conditions (distance, target illumination, object rotational phase…) will only be met once. As a result, careful planning and testing must be conducted to ensure that the important observations, necessary to meeting the mission's science requirements, will be executed properly and will result in appropriate data being collected.

To that end, we have developed the Science Encounter Sequence Simulator (SESS) tool. Based on the NAIF's SPICE Toolkit and written in Python 3, it allows one to model the Lucy spacecraft as it flies by one of its targets, and to make it process a series of commands to adjust its attitude, the pointing of the instruments, and trigger acquisitions. The code outputs attitude data for the spacecraft and the Instrument Pointing Platform (IPP), as well as the position of the scan mirror of the L'Ralph instrument.

Several of Lucy's Level 1 science requirements involve observing a certain fraction of the asteroid's surface at a characteristic resolution. To help us evaluate if those requirements are met, SESS models the surface of the target asteroid (using either a simple tri-axial ellipsoid, or a more complex shape provided as a Digital Shape Kernel). For each observation, we determine which points of the object's surface are in an instrument's field of view, and determine the resolution at that point, including degradation due to the effects of imperfect pointing stability, jitter, and smear. Using outputs from SESS, we can map the best resolution achieved at each location on the asteroid, as well as produce various other pieces of information for each observation (e.g., phase and incidence angles, local time of day) that allow the Science Team to audit an observation sequence and make recommendations for adjustments and/or request implementation of additional observations.

Planning observations gets increasingly difficult when trying to account for various sources of uncertainty. For example, imperfect pointing might result in degradation of the expected data (smaller observed area and/or worse resolution). Additionally, fluctuations in the timing of command executions can result in collisions between consecutive instructions. SESS allows us to thoroughly test the resilience of a sequence of observations against uncertainties by performing hundreds of simulations with slight variations of parameters such as spacecraft delivery, target size/shape, or knowledge of the relative position of the spacecraft and asteroid. Since the inception of the mission, SESS has proven to be an extremely valuable tool to guide the development of Lucy's activities that maximize the mission's science return.

Keywords: Lucy, Trojan Asteroids, Science Planning, Simulation

Acronyms/Abbreviations

C-matrix Kernel (CK)
Digital Shape Kernel (DSK)
Instrument Pointing Platform (IPP)
Planetary Constants Kernel (PCK)
Science Encounter Sequence Simulator (SESS)
Spacecraft (SC)
Spacecraft and Planet Kernel (SPK)
Terminal Tracking Camera (TTCAM)

1. Introduction

Lucy is NASA's 13th Discovery-class mission [1]. It will be the first spacecraft to visit the Trojan asteroids of Jupiter, with encounters planned both in the L4 and L5 swarms (Figure 1). Additionally, Lucy explored the Main Belt asteroid (152830) Dinkinesh in November 2023 [2] (also see paper ID # 540 by B. Keeney), and it is currently approaching (at the time of writing this paper) a second Main Belt asteroid, (52246) Donaldjohanson, for an encounter on 20 April 2025. Following those two "rehearsal" encounters, it will visit (3548) Eurybates and (15094) Polymele in 2027, (11351) Leucus and (21900) Orus in 2028, and finally the near-equal mass binary (617) Patroclus – (617) I Menoetius in 2033.

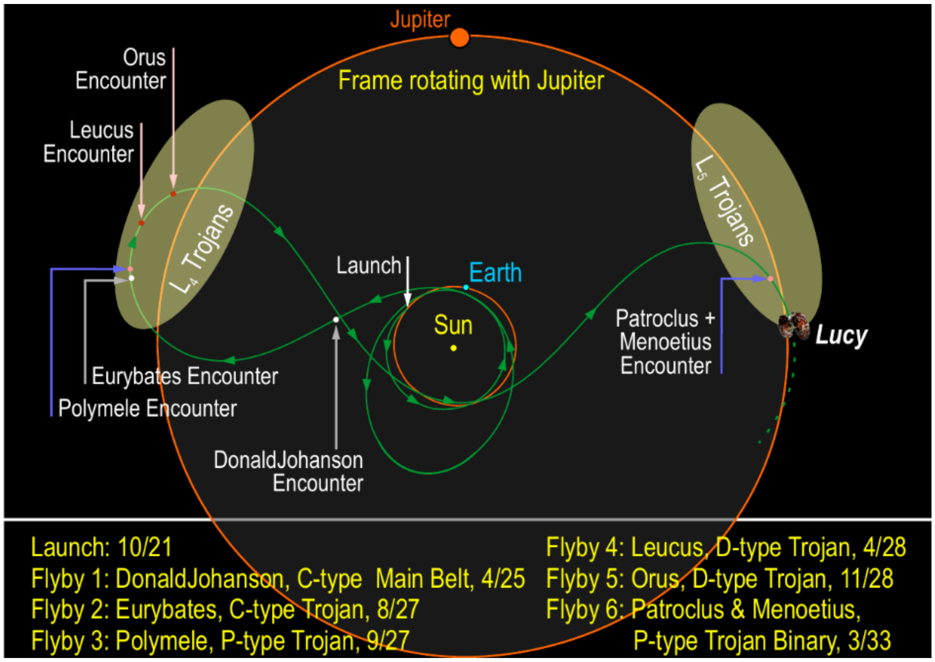

Fig. 1. Lucy's journey to the Jupiter Trojans.

Throughout this 12-year journey, Lucy will survey not only a diversity of object sizes (from ~14km-radius Polymele to ~65km-radius Patroclus), but also a diversity of spectral types (with fly-bys of C-, D-, P-type objects). The visit of objects of similar size but different spectral types (e.g. Eurybates and Orus), as well as objects of different size but with similar spectral types (e.g. Polymele and Patroclus-Menoetius) will considerably enhance our understanding of the origin and evolution of these objects.

To learn as much as possible about this unexplored population of asteroids, Lucy's science objectives are composed of 17 Level 1 Science Requirements (e.g. [3]). Those have been designed to help us understand the geology, surface composition, and internal structure of the Trojan asteroids, as well as measure their mass and detect potential satellites. This ambitious plan is rendered particularly difficult by the encounters being rapid flybys. This has two major implications: 1) a given observation condition (e.g. phase angle) will only happen once per encounter, and 2) the window of opportunity to perform certain observations will be very limited (e.g. our highest-resolution imaging will only be achievable during the innermost few hours around closest approach). As such, meticulous planning of spacecraft activities (pointing and instrument acquisitions) is necessary to ensure that adequate data can be acquired to meet our science requirements.

Additional complications arise from a series of uncertainties, such as:

- Uncertainties in the relative position of Lucy with respect to the target asteroid
- Uncertainties in the delivery of the spacecraft
- Uncertainties in the shape and pole orientation of the target

One consequence of these uncertainties is that there will be an error in the spacecraft's knowledge of its true range to the target. Because instrument commands are triggered on *distance* inside ±4 days of passage at closest approach, instrument data acquisitions will happen at a distance slightly different than originally intended, resulting in potentially worse resolution (if an acquisition is triggered too far) and/or less observed area (if an acquisition is triggered too close). Additionally, these uncertainties will result in imperfect pointing and tracking of the asteroid, which will affect the quality of the data (e.g. degraded resolution due to smear).

Testing our observation sequences against all these sources of uncertainties is crucial to ensure that we will be able to meet our science requirements. To that end, we have developed the Science Encounter Simulation Software, a computer simulator that allows us to model Lucy's flyby of a target asteroid, execute instrument commands, and produce estimates of instrument data.

2. Description of the software

SESS was originally developed by Lucy's PI Hal Levison. Written in FORTRAN in the early stages of the mission, it was not designed to easily interface with other tools and products being developed for other aspects of mission planning. While it was of great use to help us assemble the first drafts of our observation sequences [4], it was decided to rewrite it with a more modern language (Python 3) and to make extensive use of the NAIF SPICE library (SpiceyPy). The latter is allowing us to use official mission kernels for spacecraft trajectories, reference frames, instrument technical details, asteroid shapes, etc…

SESS models the attitude of the spacecraft throughout the encounter, as well as that of the IPP. The IPP is a 2-axis gimbal on which the instruments are mounted, allowing us to adjust the pointing of the instruments while maintaining the orientation of the spacecraft. In addition, SESS can perform instrument data acquisition, and produce an estimate of the resulting data by combining it with an asteroid surface model. A summary of the different steps of a SESS run is shown in Figure 2.

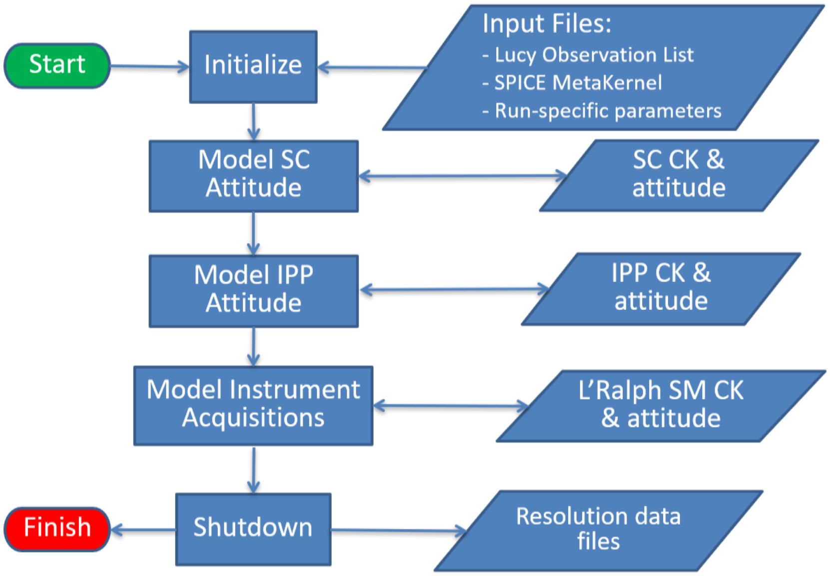

Fig. 2. SESS execution flow diagram

2.1 Inputs

SESS takes as input an SPK containing the position and velocity of Lucy and that of a target asteroid, generally in the J2000 frame. The other principal inputs are:

- A frame kernel, defining the SC, IPP, and instruments frames, and how they relate to each other
- Instrument kernels, defining the field of views of the instruments as well as technical details such as pixel size and iFOVs.
- A shape model for the asteroid, in the form of a PCK and optional DSK
- A Lucy Observation List (LOL). This is a text file containing instructions to be executed by SESS, such as adjusting the pointing of the IPP or performing instrument acquisitions. This file is produced by the Trojan Planning File Generator software (see paper ID #553 by E. Birath et al.)
- A parameter file specifying run-specific information such as the time period to model, the number of surface elements for the target, output filenames, and other technical information not listed in kernels (e.g. SC maximum rotation rate)

2.1 Modelling the SC and IPP attitudes

The input trajectory SPK is combined with the information in the Lucy frame kernel to produce a C-kernel giving the orientation of the spacecraft in space as a function of time. The orientation of the spacecraft during a SESS run can be adjusted by processing input commands. When modelling a Trojan flyby, we generally have 4 instructions:

- Set the initial orientation of the spacecraft. This attitude has the spacecraft's antenna pointed towards Earth, and uses the IPP to maintain pointing to the target

- Set the SC into Target Track. This makes the spacecraft rotate around the target while tracking the nadir point
- Pitch back the spacecraft. This rotates the SC backwards after close approach, in order to orient the solar panels towards the sun
- Return the spacecraft to Earth pointing.

Once we have modelled the SC's attitude throughout the encounter, we proceed to do the same for the IPP. The IPP attitude is initialized to point at the asteroid's center of mass throughout the simulation time, taking into account the previously computed SC attitude. The pointing of the IPP can then be modified through instructions in the LOL. At the end of the run, SESS produces a CK representing the orientation of the IPP with respect to the SC.

2.2 Modelling the target

To produce an estimate of the data that would result from a sequence of instrument acquisition, SESS generates a surface model of the asteroid on which to project each instrument's field of view. If only a PCK is provided, SESS computes a Delaunay triangulation of the surface using the number of points supplied in the parameter file. It then computes the barycenter of each facet to generate a series of pairs (facet center, facet area) that discretize the surface of the body. If a complex shape is provided via a DSK, SESS directly extracts the content of the DSK to generate similar pairs.

2.3 Modelling instrument acquisitions

Triggering instrument acquisitions is performed via instructions in the LOL. Lucy's payload consists of three science instruments [5]:

- L'LORRI, a narrow-angle (~5×5 mrad) panchromatic camera, used to get the highest-resolution panchromatic images of the Lucy targets
- L'TES, a Fourier-transform, interferometric point-spectrometer which collects hyperspectral Thermal Infrared (6-100 μm) spectra. It is used to determine thermal inertia and thermo-physical properties of the surfaces of the Lucy targets.
- L'Ralph, which consists of two instruments in one with a shared optical path:
  - MVIC, a visible wavelength multicolor imager, which is a multi-band (5 color filters, plus one panchromatic band) push-broom camera.
  - L'LEISA, the infrared mapping spectroscopy facility, which is an IR HgCdTe array with a linear wedge filter which operates as a push-broom spectrometer.

L'Ralph is equipped with a scan mirror mechanism, which allows the instrument to observe different parts of the sky without having to adjust the pointing of the SC or the IPP.

Lucy is also equipped with a pair of Terminal Tracking Cameras (the second camera is a backup in case the first one was to encounter issues). This camera is used primarily for navigation and pointing purposes, but is also used for science as it can provide wide-angle (field of view ~152×190 mrad) panchromatic images. In particular, it will allow us to capture the full surface of most of our targets near close approach.

Each instrument is modelled in SESS based on the information provided in the input instrument and frame kernels (e.g. field of view shape and size, frame orientation with respect to the IPP, relative position of the various bands and channels for MVIC and L'LEISA, …). For each instrument acquisition instruction in the LOL, SESS extracts exposure-specific parameters such as the exposure duration, number of frames to take, or the Scan Mirror start/stop angles for L'Ralph. With the information from the SPK, as well as the calculated orientation of the SC and IPP (Section 2.1), SPICE routines can be used to determine if surface elements are visible from the point of view of Lucy, and if they are illuminated or in the shadows. For the specific case of L'Ralph, a preliminary step is required to model the position of the scan mirror during the acquisition, as the field of view of L'LEISA and MVIC is defined with respect to the scan mirror (SESS outputs an additional CK containing the position of the scan mirror throughout the run).

For each visible and illuminated surface element, we check if it falls within the field of view of the instrument doing the acquisition. If it does, we then calculate the resolution R achieved at that point as

$$R = d * \tan(PSF_{eff}) \qquad (1)$$

where d is the distance to the surface element and PSF_{eff} is the Point Spread Function of the instrument degraded by the effects of jitter, and smear resulting from motion of the surface during the exposure. Additionally, we compute a *projected* resolution R_{proj} resulting from the curvature of the body

$$R_{proj} = \frac{R}{\cos e} \qquad (2)$$

where e is the emission angle (the angle between the SC to surface vector and the local normal vector to the surface). The corresponding resolutions are saved in a array that stores, for each instrument, the best resolution achieved at each surface element of the asteroid. At the end of a run, each array is written in a specific resolution data file that can be used to produce resolution maps (Figure 3).

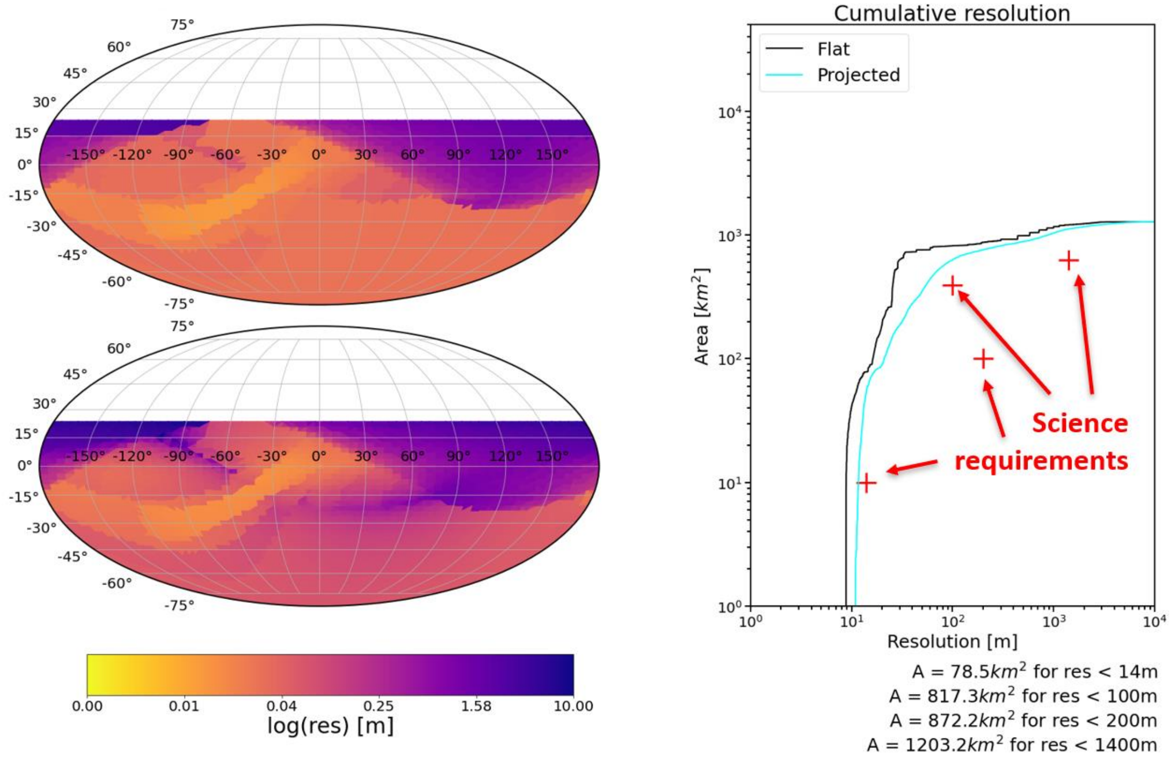

Fig. 3. An example resolution map of all panchromatic observations, plotted from a resolution data file output from a SESS run of the Polymele LOL. Left: best resolution achieved at each point on the surface, represented by a longitude and latitude grid with Mollweide projection. The bottom map shows the resolution that takes into account the effects of curvature. Right: cumulative resolution showing the observed area as a function of resolution. The red crosses show our science requirements based around panchromatic observations (see [3] for details).

3. Testing the impact of uncertainties

As discussed in the introduction, there are several sources of uncertainties that will affect the data that may result from a given LOL. To ensure that our planned observations will give us the data we need to meet our science requirement, we have designed a Monte-Carlo process in which we run a given LOL a total of 1000 times with varied inputs for each run. The parameters we vary are:

- Delivery SPK (provided by NAV)
- Asteroid PCK
- SC knowledge SPK

The SC *knowledge* SPK is a secondary SPK that we load into SESS and which contains the SC's "understanding" of where it is with respect to the target. During an actual encounter, the SC will have an onboard ephemeris that contains our best estimate of the trajectory it's on (we call it FKU for Final Knowledge Update). At around 2 hours prior to close approach, the TTCAM will start feeding images to a centroiding algorithm that will look for the asteroid [6]. Once it detects the object, it first computes a center of brightness based on all the illuminated pixels that are estimated to be part of the target. It then estimates the position of the asteroid's center of mass and provides a correction to the FKU, progressively converging towards the *true* position of the center of mass. We build our *knowledge* SPKs by stitching an FKU (delivered by NAV as a perturbation around the delivery SPK) with outputs from a centroiding simulator that mimics the response of the centroiding system onboard Lucy.

As explained earlier in this paper, for the innermost 8 days of the encounter, activities in the LOL are triggered on range. For instance, if a L'LORRI observation has a trigger range of 2000km, the observation will be triggered when the SC *thinks* it is 2000km from the target. But due to uncertainties, that might happen when in reality the SC is slightly farther or slightly closer. This also affects pointing. If we ask the IPP to point directly at the asteroid's center of mass, it will point where it *thinks* it is (Figure 4).

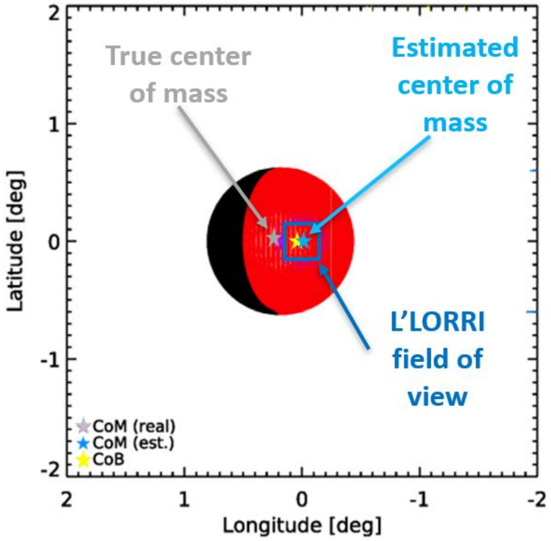

Fig. 4. Visualisation, using SESS outputs, of the pointing error resulting in the SC's imperfect knowledge of the position of the asteroid's center of mass. The blue square shows the field of view of L'LORRI, pointed to the estimated center of mass, offset from the real one.

Our Monte-Carlo testing of the sequence allows us to quantify how those fluctuations in SC knowledge, actual delivery, and variations in the targets shape and pole orientation, affect the resolution data files produced by SESS. If we determine that a science requirement is not met in more than 3 out of 1000 runs, we make adjustments to the sequence by shifting or adding observations.

4. Conclusion

The Science Encounter Simulation Software is a versatile tool that has allowed us to perform extensive planning of Lucy's flybys. From initial development of the observation sequences to their orders of magnitude more complex versions currently being assembled, SESS has helped us find the best strategies through which adequate data can be acquired at all targets. Its ability to ingest both a "truth" and "knowledge" trajectory has allowed us to ensure observation sequences are robust to various sources of uncertainties. It has proven to be a very valuable asset contributing to the success of the Lucy mission.

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