18th International Conference on Space Operations, Montreal, Canada, 26 - 30 May 2025.

SpaceOps-2025, ID # 533

Lucy's Donaldjohanson Encounter Science Planning and Sequencing

Emma Birath[a*], Brian Keeney[a], Joel Parker[a], Jon Pineau[b], Julien Salmon[a], Ishita Solanki[a], John Spencer[a], Zach Talpas[a], Michael Vincent[a], and the Lucy SOC

[a] *Solar System Science & Exploration, Southwest Research Institute, Boulder, CO. USA.*
[b] *Stellar Solutions, Inc. Denver CO. USA.*
* Corresponding Author (emma.birath@swri.org)

Abstract

En route to visit Trojan asteroids in Jupiter's L4 and L5 swarms, NASA's Lucy spacecraft has already successfully encountered the small main-belt asteroid (152830) Dinkinesh in November of 2023, and the team is now getting ready for the next encounter on April 20, 2025. The asteroid (52246) Donaldjohanson, named after the discoverer of the famous hominid fossil Lucy, is a ~4 km sized inner main-belt asteroid. Donaldjohanson will be the target for a full rehearsal for our team before the first Trojan encounter in 2027. Unlike the Dinkinesh encounter which was first-and-foremost an engineering test, the Donaldjohanson flyby will be treated as a full science packed encounter. To the extent possible with a different flyby geometry, it is designed to be a close replica of a later flyby of Trojan asteroid (15094) Polymele. The instruments will collect gigabytes of data and exercise Lucy's pointing platform capabilities to perform mosaics and scans and track secondary bodies.

With this flyby, the team is entering a new paradigm for the science planning and sequencing processes. The Science Operations Center (SOC) designed and built the uplink tools and processes in such a way to allow closer involvement by the science team in the early sequencing, and facilitate handoffs between the science team and the SOC. Similar to heritage missions such as New Horizons, the science team and working groups develop Measurement Techniques: broad descriptions of desired observations to meet the mission's formal science requirements, while working with the SOC to develop more detailed Science Activity Plans that document how the observations are executed in practice. But on the Lucy mission, the science team now has access to the SOC Trojan Planning File Generator (TPFG), which is a new web-based sequencing and scheduling tool. A science team sequencer builds the initial science timeline, and the TPFG session is handed off between the science team and the SOC as needed. As the sequence matures, the SOC performs the standard testing and develops review products for the science and payload teams, before delivering the sequence to the Mission Operation Center for further simulations and testing. This paper will focus on the new science planning tools and processes and will highlight some lessons learned and planned improvements for the upcoming Trojan encounters.

Keywords: Lucy, Trojan Asteroids, Science Planning, Sequencing

Acronyms/Abbreviations

Donaldjohanson (DJ)
Science Operations Center (SOC)
Instrument Pointing Platform (IPP)
Terminal Tracking Camera (TTCam)
Program Level Requirements Appendix (PLRA)
Measurement Technique (MT)
Science Activity Plan (SAP)
Trojan Planning File Generator (TPFG)
Virtual Machine Languate (VML)
Science Encounter Simulation Software (SESS)
Instrument Constraint Checker (ICC)
Satallite Tool Kit (STK)
Field of View (FOV)

1. Introduction

The Lucy mission is part of NASA's Discovery program, and the spacecraft launched in October of 2021. Lucy will perform five flybys of Trojan asteroids, which are asteroids in the Lagrange points of Jupiter never before explored. The first Trojan flyby is taking place in August of 2027. Leading up to the first encounter, the Lucy team has had two rehearsal opportunities with main belt asteroids. The first one, in late 2023, is described in another paper by Keeney et al [1] presented at this same conference. At the time of writing this paper, the planning and sequence implementation for the second rehearsal flyby of asteroid Donaldjohanson (DJ) is complete. Optical navigation images are coming down daily and the team is eagerly awaiting encounter day!

In the planning and sequencing for this encounter, the Science Operations Center (SOC) utilized the full set of software and processes designed and developed for our Trojan asteroid encounters. Many have deep heritage from earlier New Horizons encounters, but they've been significantly improved and modernized. These tools and processes will be described in this paper, with emphasis on differences and lessons learned to be addressed for the upcoming Trojan asteroid flybys.

2. The Lucy spacecraft and instrument suite

The Lucy spacecraft was built by Lockheed Martin. Figure 1 shows the spacecraft, the instrument pointing platform, and the two large solar arrays, each one measuring about 7.3m (24 ft) in diameter. When reaching its maximum distance from the Sun of 5.71 AU, Lucy will be the farthest spacecraft utilizing solar arrays for power.

Lucy has a suite of remote sensing instruments which are all mounted onto the instrument pointing platform (IPP). Based on the New Horizon's LORRI (LOng Range Reconnaissance Imager) instrument, the Lucy version of the instrument is referred to as L'LORRI. It is the high-resolution panchromatic imager used for both science and optical navigation. L'LORRI will provide the most detailed images of the target surfaces. The instrument is critical in satellite searches, determining size and frequency distribution of craters and other landforms, and determining the shape of Lucy's targets.

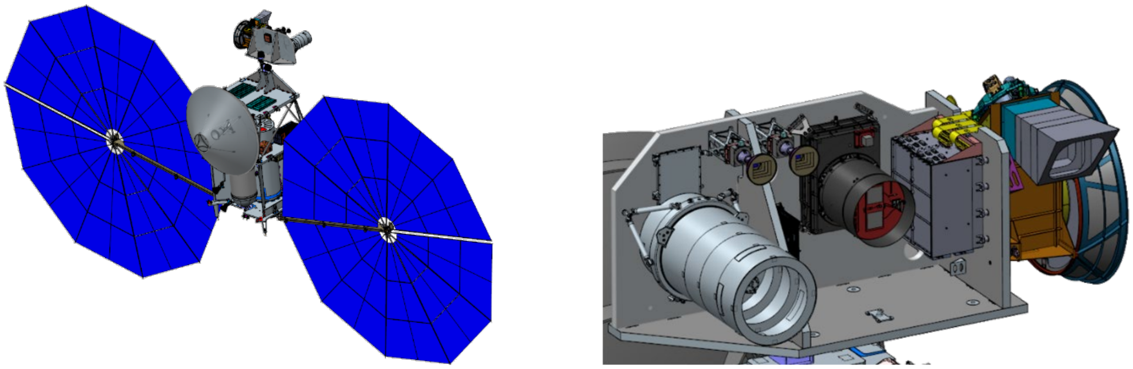


Figure 1 Lucy spacecraft and IPP

L'Ralph has heritage from New Horizons Ralph and OSIRIS-REx's OVIRS. It consists of two instruments in one. MVIC (Multispectral Visible Imaging Camera) is a visible to near-infrared imager, and LEISA (Linear Etalon Imaging Spectral Array) is an infrared spectrometer. L'Ralph will help us determine surface compositions and will look for organics, ices, and hydrated minerals.

L'TES (Thermal Emission Spectrometer) detects far infrared radiation emitted by asteroids and acts like a remote thermometer. It will take temperature measurements at various points on the asteroids to study its surface properties.

TTCam (Terminal Tracking Camera) is part of the Terminal Tracking System (TTS) which will be used to autonomously update the onboard knowledge of the spacecraft-relative target location [4] around the time of closest approach. The wide-angle field of view (FOV) will allow it to capture the full target at the time of closest approach for all encounters, providing valuable science data. TTCam will collect regular cadence imaging during the hours around closest approach. The images are analysed by a centroiding algorithm and then passed on to the State Estimator which provides the estimated target position, which is then used by the IPP to continuously track target through encounter. This onboard state estimation is a significant improvement from New Horizons where we had to take large mosaics of dark space to ensure we would capture the targets with large navigation uncertainties. The successful performance of the TTS was demonstrated at the last encounter rehearsal flyby of asteroid Dinkinesh [1,2]. The TTCam data will also be used for science and the wide FOV will help with shape modeling.

3. The DJ Flyby Rehearsal

Of all the planned Trojan encounters, the second flyby which is of asteroid Polymele is the most stressing case with a small target (30 km diameter) and a close flyby distance (434 km). The smaller target size requires a closer flyby distance for radio science mass determination, compared to the other Trojans. It was therefore decided to use the Polymele flyby as the basis for the full encounter rehearsal at Donaldjohanson. At the start of DJ planning, a draft version of a Polymele flyby sequence had already been developed. This sequence was used as a starting point for the DJ encounter development. Some adaptations had to be made to the sequence however, as there are several unavoidable differences between the Polymele and the DJ encounters.

Asteroid Donaldjohanson is smaller than the Trojan Asteroids, measuring around 4 km in diameter. The terminal tracking camera is therefore not expected to resolve the target until ~ ½ hr before the time of closest approach. For the DJ encounter we're configured to start using the onboard state estimation solution as soon as the instrument acquires the target and a solution is available, while at the Trojans state estimation use begins at a pre-determined time.

Another significant difference between DJ and Polymele encounters is the flyby geometry. For DJ we're approaching at a low phase angle (13° at E-4 days compared to 81° for Polymele) which means that we cannot continue tracking the target past closest approach, as that would put the instrument boresights uncomfortably close to the Sun. For DJ we therefore have to turn the instruments away from the target right before the time of closest approach, by placing the IPP in a Sun avoidance position. The spacecraft however will proceed with the maneuver required during Trojan asteroid encounters to track the target before the pitchback maneuver a few minutes after closest approach which allows us again to point the HGA back at Earth and the solar panels back at the Sun.[3]

Table 1. Flyby geometry

	C/A date	Appr. Target Diam (km)	Sun Dist (AU*)	Approach Phase** (deg)	C/A Dist (km)	C/A Velocity (km/sec)
Donaldjohanson	**2025-04-20**	**4**	**2.1**	**13**	**960**	**13.4**
Eurybates	2027-08-11	64	5.7	81	750	5.8
Polymele	**2027-09-15**	**30**	**5.7**	**81**	**434**	**6.1**
Leucus	2028-04-18	41	5.6	103	1000	5.9
Orus	2028-11-11	51	5.3	126	1000	7.1
Patroclus-Menoetius	2033-03-03	113/104	5.4	56	1091	8.8

* AU = Astronomical Unit ** 4 days before closest approach

The flyby velocities also differ, and the DJ relative velocity is about twice that of the Polymele-Lucy relative velocity. A larger close approach distance for DJ (960 km) was chosen to ensure the spacecraft slew rates during the encounter mimic the fastest slew rates we may see at the Polymele encounter (taking into consideration 3-sigma delivery uncertainties).

The closer Sun distance (2AU compared to 5.7AU at Polymele) also leads to a different thermal environment. The Ralph LEISA instrument is therefore not expected to be cool enough to meet science requirements. To mitigate this and increase chance of getting some useful data at the time of closest approach, we place the IPP in a 'Ralph friendly' position for a few hours before closest approach, pointing the Ralph radiator away from the solar arrays which during cruise has shown to significantly cool the LEISA instrument. This is done for a period during approach when quality science data is limited anyway, due to the small size of DJ and its long (250 hour) rotation period which means that images taken an hour or two before close approach would show the same side of DJ as the highest-resolution images.

Other than the above-mentioned adaptations, the DJ command sequence is a close replica to the Polymele encounter. We're collecting approximately the same amount of data, as we continue recording data even during the off nadir pointing for Ralph cooling, and after the Sun avoidance maneuver at the time of closest approach. Not all the data will be transferred off the recorder and downlinked, but all the data is stored to mimic memory storage and handling. We are also operating the IPP to its full extent, performing mosaics and scans like those at Polymele though the timing of these has been changed to avoid the off-pointed periods. During approach, we're performing optical navigation with the L'LORRI instrument, exercising the full process of orbit determination and trajectory correction maneuvers, and the final update to the onboard ephemeris which happens 4 days before closest approach.

The DJ flyby has no science requirements directly tied to it, as the purpose of it is first-and-foremost a rehearsal. There were a few exceptions, such as the use of shorter exposure times, but in general the sequence was not optimized for DJ. Scan rates and mosaic sizes were kept as designed for Polymele to appropriately rehearse the most stressing case of a Trojan flyby.

4. Lucy Encounter Planning

The Lucy mission has a set of science requirements to meet for each Trojan asteroid encounter. The Science Planning process is requirements driven. The requirements are tracked by the project in the PLRA (Project Level

Requirements Appendix), but also documented in the SOC Confluence system, which is a collaborative communication and documentation sharing system that is part of the Atlassian system. The Atlassian system, including its Confluence component, is heavily used by science team and SOC for documentation, load development tracking and signoffs, meeting notes, task tracking, action items, etc.

Years before an encounter the science team take the requirements and write Measurement Techniques (MTs) which are detailed descriptions of the observations that are needed to meet the science requirements. The MTs are all tracked in Confluence and linked to the requirements. In addition to requirements, the science team also have ‘desirements’ that are also tracked in the MTs. The MTs have supporting plots, graphics, diagrams, and any details needed to capture the background and considerations that went into the MTs.

Science Activity Plans (SAPs) flow down from the MTs and capture the detailed commanding information needed by science and SOC sequencers to build the command load. The SAPs will also contain commanding details for the IPP, describing the pointing needed to meet the science objectives, scan or mosaic details, etc. Special requests for additional S/C or instrument housekeeping telemetry are also tracked in the SAPs. The SAPs are linked back to parent MTs.

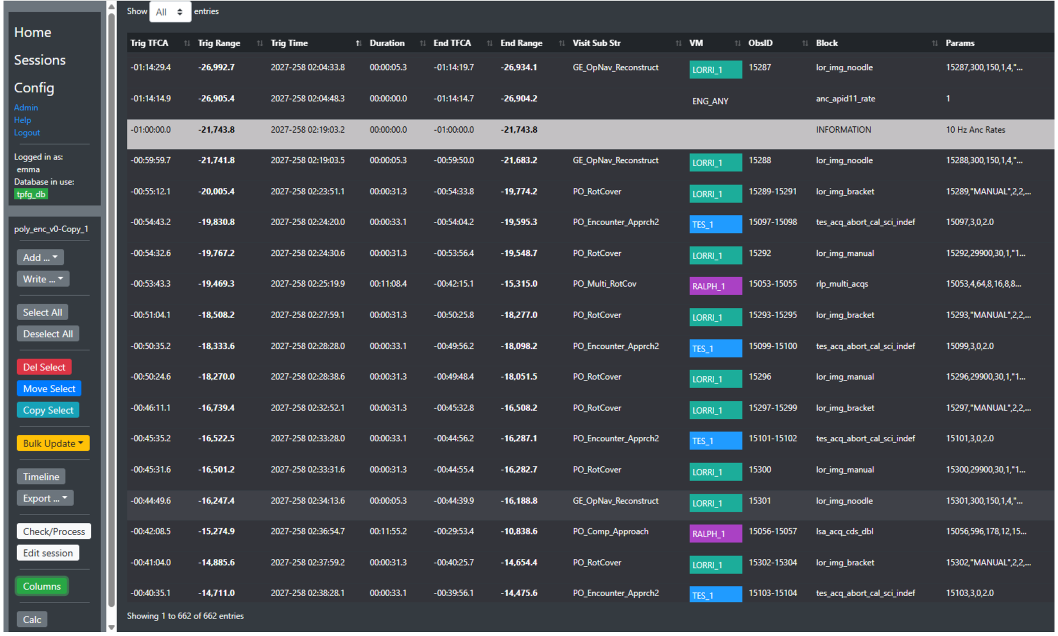
The processes described here all have close heritage from New Horizons with the main difference and improvement is in using Confluence for the documents and communication.

5. Lucy Encounter Sequencing

5.1 The Trojan Planning File Generator

For building command loads, the SOC developed a piece of software called the Trojan Planning File Generator, or TPFG. It is written in python, using the powerful Django web framework, with a postgres database backend. The tool runs on our SOC server and can be accessed remotely by sequencers. It writes out the sequence products that are delivered to the MOC for both cruise loads and encounter loads. The deliverable (whether for cruise or encounter loads) is the TPF (Trojan Planning File).

Onboard the spacecraft we have science and engineering VML (Virtual Machine Language) block libraries, which are libraries of reusable command macros that take a set of input parameters to execute desired payload activities, IPP re-positions, and spacecraft activities. The TPFG user interface lets the sequencers build the timeline of activities, and schedule all the block calls needed to accomplish the objectives in the SAPs and MTs, to ultimately meet science requirements. The interface lets you easily add, move, and copy activities, as well as write out and ingest “snippets”, which are multi-block activities that are frequently repeated. There is a limited “bulk update” feature that allows you to select multiple instructions and update things like the SAP ID, or comments. In addition to block calls, the user can also add “directives” which are structured comments intended to communicate and coordinate the timing of some MOC-sequenced activities like reaction wheel speed desaturation activities (desats) and spacecraft attitude updates.



Logged in as: emma
Database in use: tpfg_db

poly_enc_v0-Copy_1

Show All entries

Trig TFCA	Trig Range	Trig Time	Duration	End TFCA	End Range	Visit Sub Str	VM	ObsID	Block	Params
-01:14:29.4	**-26,992.7**	2027-258 02:04:33.8	00:00:05.3	-01:14:19.7	**-26,934.1**	GE_OpNav_Reconstruct	LORRI_1	15287	lor_img_noodle	15287,300,150,1,4,"...
-01:14:14.9	**-26,905.4**	2027-258 02:04:48.3	00:00:00.0	-01:14:14.7	**-26,904.2**		ENG_ANY		anc_apid11_rate	1
-01:00:00.0	**-21,743.8**	2027-258 02:19:03.2	00:00:00.0	-01:00:00.0	**-21,743.8**				INFORMATION	10 Hz Anc Rates
-00:59:59.7	**-21,741.8**	2027-258 02:19:03.5	00:00:05.3	-00:59:50.0	**-21,683.2**	GE_OpNav_Reconstruct	LORRI_1	15288	lor_img_noodle	15288,300,150,1,4,"...
-00:55:12.1	**-20,005.4**	2027-258 02:23:51.1	00:00:31.3	-00:54:33.8	**-19,774.2**	PO_RotCover	LORRI_1	15289-15291	lor_img_bracket	15289,"MANUAL",2,2,...
-00:54:43.2	**-19,830.8**	2027-258 02:24:20.0	00:00:33.1	-00:54:04.2	**-19,595.3**	PO_Encounter_Apprch2	TES_1	15097-15098	tes_acq_abort_cal_sci_indef	15097,3,0,2.0
-00:54:32.6	**-19,767.2**	2027-258 02:24:30.6	00:00:31.3	-00:53:56.4	**-19,548.7**	PO_RotCover	LORRI_1	15292	lor_img_manual	15292,29900,30,1,"1...
-00:53:43.3	**-19,469.3**	2027-258 02:25:19.9	00:11:08.4	-00:42:15.1	**-15,315.0**	PO_Multi_RotCov	RALPH_1	15053-15055	rlp_multi_acqs	15053,4,64,8,16,8,8...
-00:51:04.1	**-18,508.2**	2027-258 02:27:59.1	00:00:31.3	-00:50:25.8	**-18,277.0**	PO_RotCover	LORRI_1	15293-15295	lor_img_bracket	15293,"MANUAL",2,2,...
-00:50:35.2	**-18,333.6**	2027-258 02:28:28.0	00:00:33.1	-00:49:56.2	**-18,098.2**	PO_Encounter_Apprch2	TES_1	15099-15100	tes_acq_abort_cal_sci_indef	15099,3,0,2.0
-00:50:24.6	**-18,270.0**	2027-258 02:28:38.6	00:00:31.3	-00:49:48.4	**-18,051.5**	PO_RotCover	LORRI_1	15296	lor_img_manual	15296,29900,30,1,"1...
-00:46:11.1	**-16,739.4**	2027-258 02:32:52.1	00:00:31.3	-00:45:32.8	**-16,508.2**	PO_RotCover	LORRI_1	15297-15299	lor_img_bracket	15297,"MANUAL",2,2,...
-00:45:35.2	**-16,522.5**	2027-258 02:33:28.0	00:00:33.1	-00:44:56.2	**-16,287.1**	PO_Encounter_Apprch2	TES_1	15101-15102	tes_acq_abort_cal_sci_indef	15101,3,0,2.0
-00:45:31.6	**-16,501.2**	2027-258 02:33:31.6	00:00:31.3	-00:44:55.4	**-16,282.7**	PO_RotCover	LORRI_1	15300	lor_img_manual	15300,29900,30,1,"1...
-00:44:49.6	**-16,247.4**	2027-258 02:34:13.6	00:00:05.3	-00:44:39.9	**-16,188.8**	GE_OpNav_Reconstruct	LORRI_1	15301	lor_img_noodle	15301,300,150,1,4,"...
-00:42:08.5	**-15,274.9**	2027-258 02:36:54.7	00:11:55.2	-00:29:53.4	**-10,838.6**	PO_Comp_Approach	RALPH_1	15056-15057	lsa_acq_cds_dbl	15056,596,178,12,15...
-00:41:04.0	**-14,885.6**	2027-258 02:37:59.2	00:00:31.3	-00:40:25.7	**-14,654.4**	PO_RotCover	LORRI_1	15302-15304	lor_img_bracket	15302,"MANUAL",2,2,...
-00:40:35.1	**-14,711.0**	2027-258 02:38:28.1	00:00:33.1	-00:39:56.1	**-14,475.6**	PO_Encounter_Apprch2	TES_1	15103-15104	tes_acq_abort_cal_sci_indef	15103,3,0,2.0

Showing 1 to 662 of 662 entries

Figure 2 Trojan Planning File Generator (TPFG)

TPFG checks the sequence for invalid blocks or input parameters. It determines block duration based on input parameters and flags block overlaps within an instrument virtual engine. It calculates data volumes and assigns ‘Obs IDs’ to individual acquisitions, which are used on Lucy to track downlinked observations to the planned activity, so that data users can easily link an image back to its parent SAP and MT(s).

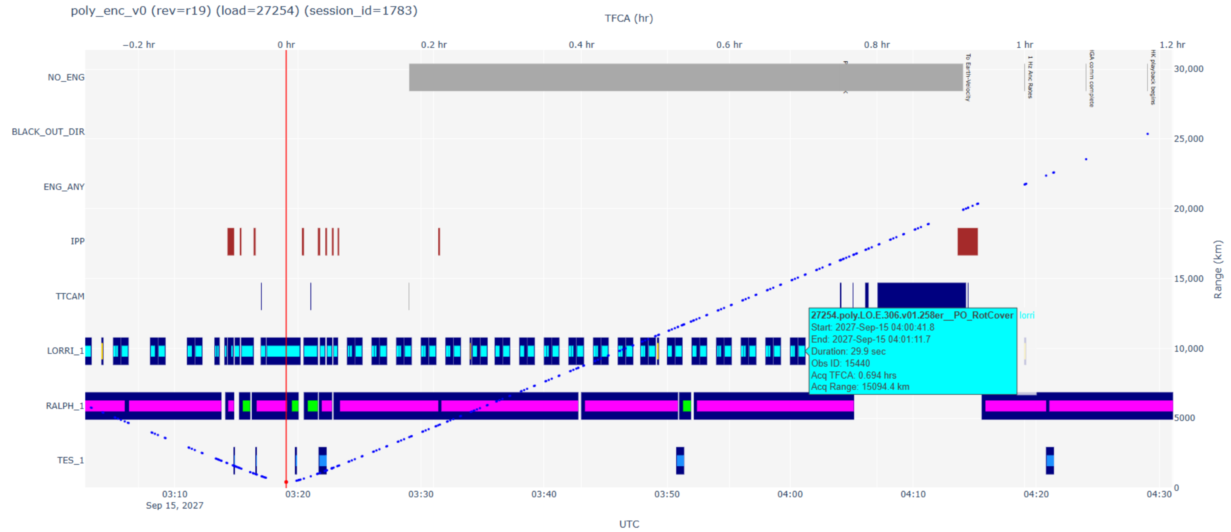
A limited set of the spacecraft (engineering) blocks are available for use by the SOC in the TPFG interface, allowing SOC to command the IPP and request specific telemetry rates for spacecraft APIDs like attitude quaternions and IPP gimbal telemetry.

On Lucy, the close approach command loads are range based, instead of executed by time. Blocks are kicked off when the onboard state estimation determines that Lucy has reached a specified ‘trigger range’. TPFG uses NASA's Navigation and Ancillary Information Facility’s observation system, SPICE, to calculate time-to-range and range-to-time conversions so that the users can work in either the time or range domain. It also ensures there is enough padding between block calls to account for the elasticity of the command load, which is a result of the onboard state estimation that may shift a block call earlier or later when range estimates are updated.

5.2 The Interactive HTML Timeline Visualizer

An encounter command load, which spans 8 days around closest approach, can contain hundreds block calls, which causes the TPFG session to feel a little unwieldy. As a result, we developed a timeline visualizer component in the software. After discovering the Python module plotly, and its companion Plotly Express, with only a couple of hundred lines of code we were able to add an interactive HTML timeline visualizer to the software. Plotly automatically implements the interactive features, so you can zoom in/out and pan. You can hover on each activity to access detailed information. The data in the plot comes from the TPFG database, so any data that lives in the database can be added to the hover information. The time on the x-axis is shown in both UTC and time from closest approach in hours. Each instrument is shown on its own row on the y-axis, and there are separate rows for IPP and spacecraft activities. The range to target was added to the secondary y-axis for target proximity context.

This interactive HTML timeline has been very helpful for command load building. An added benefit is that the resulting timeline is simply an .html file that can easily be shared with the team through email or other means. The timelines have now become a standard part of the review products for the teams, to be discussed in the next section.



27254.poly.LO.E.306.v01.258er__PO_RotCover
Start: 2027-Sep-15 04:00:41.8
End: 2027-Sep-15 04:01:11.7
Duration: 29.9 sec
Obs ID: 15440
Acq TFCA: 0.694 hrs
Acq Range: 15094.4 km

Figure 3 Interactive HTML timeline visualizer for TPFG

6. Lucy Sequence Reviews

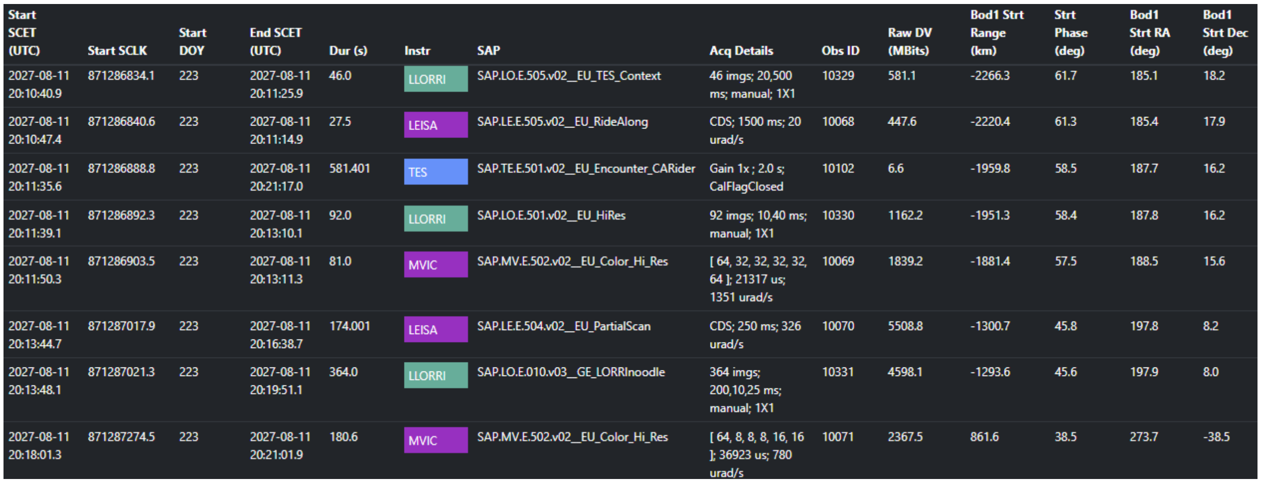
Once a sequence is built, the arguably even more arduous task of *reviewing* the command load starts. The importance of facilitating such reviews with appropriate review products for all teams cannot be understated. The SOC produces a set or review products for the science team, instrument teams, and navigation team that are very similar in nature to review products used on New Horizons, however the tools available now to create them makes this process much more efficient and less tedious and error prone. A brief summary of these products and the tools that produce them is listed here.

6.1 Instrument Constraint Checker

The SOC's instrument constraint checker (ICC) performs flight rule checks for all instruments, and it has also implemented additional checks that don't fall under an official flight rule. The output files are made available to all teams, but especially of interest of course to the instrument teams and SOC.

6.2 Audit and Image Lists

On New Horizons, to eliminate the need for teams to parse through thousands of commands in their sequence reviews, the SOC would produce observation summary spreadsheets that we would walk through during sequence audit meetings with the science, instrument, and navigation teams. Eventually scripts were written to partially automate that process. On Lucy we took one step further and built a Database Uplink Ingester Tool (DUIT) that ingests command lists output from simulations into a database. The command lists are parsed and interpreted by the software, acquisition details are stored in the database, and then a web-based Audit and Image List Tool (AILT) makes it possible for teams to view the data interactively. AILT displays a list of all acquisitions in a command load, including details like exposure durations, instrument mode, formats, binning mode, scan mirror start and stop position (for Ralph instrument) and other details that teams need to review. SPICE calculations are used to display a limited set of geometry parameters like range and phase angle for the start and end times of observations.



Start SCET (UTC)	Start SCLK	Start DOY	End SCET (UTC)	Dur (s)	Instr	SAP	Acq Details	Obs ID	Raw DV (MBits)	Bod1 Strt Range (km)	Strt Phase (deg)	Bod1 Strt RA (deg)	Bod1 Strt Dec (deg)
2027-08-11 20:10:40.9	871286834.1	223	2027-08-11 20:11:25.9	46.0	LLORRI	SAP.LO.E.505.v02__EU_TES_Context	46 imgs; 20,500 ms; manual; 1X1	10329	581.1	-2266.3	61.7	185.1	18.2
2027-08-11 20:10:47.4	871286840.6	223	2027-08-11 20:11:14.9	27.5	LEISA	SAP.LE.E.505.v02__EU_RideAlong	CDS; 1500 ms; 20 urad/s	10068	447.6	-2220.4	61.3	185.4	17.9
2027-08-11 20:11:35.6	871286888.8	223	2027-08-11 20:21:17.0	581.401	TES	SAP.TE.E.501.v02__EU_Encounter_CARider	Gain 1x ; 2.0 s; CalFlagClosed	10102	6.6	-1959.8	58.5	187.7	16.2
2027-08-11 20:11:39.1	871286892.3	223	2027-08-11 20:13:10.1	92.0	LLORRI	SAP.LO.E.501.v02__EU_HiRes	92 imgs; 10,40 ms; manual; 1X1	10330	1162.2	-1951.3	58.4	187.8	16.2
2027-08-11 20:11:50.3	871286903.5	223	2027-08-11 20:13:11.3	81.0	MVIC	SAP.MV.E.502.v02__EU_Color_Hi_Res	[64, 32, 32, 32, 32, 64]; 21317 us; 1351 urad/s	10069	1839.2	-1881.4	57.5	188.5	15.6
2027-08-11 20:13:44.7	871287017.9	223	2027-08-11 20:16:38.7	174.001	LEISA	SAP.LE.E.504.v02__EU_PartialScan	CDS; 250 ms; 326 urad/s	10070	5508.8	-1300.7	45.8	197.8	8.2
2027-08-11 20:13:48.1	871287021.3	223	2027-08-11 20:19:51.1	364.0	LLORRI	SAP.LO.E.010.v03__GE_LORRInoodle	364 imgs; 200,10,25 ms; manual; 1X1	10331	4598.1	-1293.6	45.6	197.9	8.0
2027-08-11 20:18:01.3	871287274.5	223	2027-08-11 20:21:01.9	180.6	MVIC	SAP.MV.E.502.v02__EU_Color_Hi_Res	[64, 8, 8, 8, 16, 16]; 36923 us; 780 urad/s	10071	2367.5	861.6	38.5	273.7	-38.5

Figure 4 AILT interface

6.3 STK graphics, movies, reports

The SOC uses AGI's Satellite Tool Kit (STK) for 3D visualization of the encounters. Using Python integration, producing the graphics has been mostly automated, where the user can provide an export from AILT to create graphics for each observation. Reviewers can step through the encounter graphics in their favourite graphics viewer, and it usually allows you to see them in 'movie mode' as you step through them.

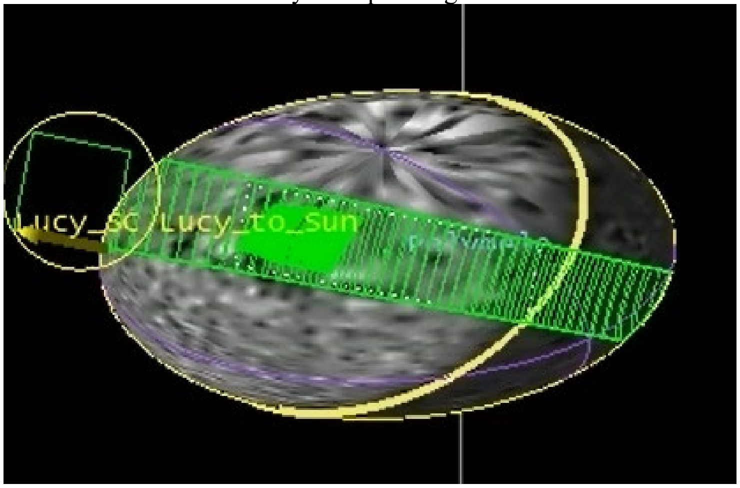


Figure 5 STK visualization of a Polymele scan

Reports of some geometry information such as boresight to Sun angles, boresight to target angles, IPP angles as a function of time are also automatically produced with our python integration. STK outputs static JPEGs of these reports, however we've recently incorporated plotly to generate interactive reports as reviewers often need to zoom in on specific time periods. This tool has the added benefit of providing the downlink and processing status of each acquisition as a quick status of executed science activities.

7 Operations Development Process Advances

7.1 Science Team Sequencers

During cruise and calibration uplink operations, Lucy SOC has operated similar to earlier missions like New Horizons, where a SOC sequencer who is trained in operations for an instrument is responsible for all the encounter commanding for that instrument, and there is one sequencer per instrument. The individual sequences are eventually merged before delivery to the MOC. For this reason, TPFG has the added feature of being able to merge sessions. This has continued to work well for cruise and calibration command loads.

For encounter loads however, on previous missions the de-conflicting after the merge of instrument sequences proved to be a significant task with time-consuming iterations. After reviews, if one instrument had to make updates, it again required careful instrument-to-instrument coordination to ensure nothing would break in the next merge.

We also wanted to have the science team be more closely involved in laying out the timeline for an encounter. The SOC sequencers may or may not be fully immersed in the early studies and considerations for an encounter. TPFG was designed with the idea in mind that the science team would develop the initial command load and the sessions could be handed off to SOC for reviews and addition of engineering activities like data retrievals (pulling data off the recorder and compressing for downlink), adjusting telemetry rates, coordinating instrument power on/offs, etc.

TPFG was therefore designed to facilitate session handoffs. At any time, a session has a single owner, and only the owner has edit permissions. Handing off a session is as easy as changing the owner (which only the owner has permission to do). Meanwhile all TPFG users can *view* all sessions regardless of ownership, to increase visualization between team members. Version control has also been significantly improved with the sessions living in TPFG instead of on individual SOC sequencer's computers.

The DJ flyby is the first flight activity that was developed using this new paradigm of using science team sequencers. How well has it worked? Developing the encounter load within a single session in TPFG has definitely eliminated the painful post-merge deconflicting. Increased visualization with the TPFG timeline visualizer has been a game changer in helping with instrument-to-instrument coordination during building of the load itself, and we have found that little needs to be done to deconflict after the load is built.

Having a single session for an encounter which only a single owner can edit at one time, does mean a lot of work for the one science sequencer. To avoid further resource crunches, the science team has assigned different science sequencers for each encounter, since planning phases for different encounters do overlap.

To make sure nothing falls through the cracks with the new paradigm, we ensured that the SOC sequencers still carefully review the command loads. This has led to the SAPs being ever-more critical means of communication, to capture intent for a sequencer who was not as closely involved in building the command load itself.

Overall, having the sequencing be done by an individual who is deeply immersed in all science team meetings and working group discussions has been a huge improvement.

7.2 Early Modeling and Sequence Testing with SESS

One of the lessons learned from New Horizons was the importance of having the tools needed to perform SOC-internal reviews of a command load before delivering the sequence to MOC. On New Horizons we relied heavily on the output of software and hardware simulations run by the MOC, which led to a lot of time-consuming iterations with the MOC. For Lucy, we designed tools that allow us to produce all the necessary review products internally, helping us to catch a most issues before delivering the first version of a sequence to the MOC.

A critical aspect of early reviews is the ability to review pointing. On Lucy we need to track not only spacecraft attitude but also the operations of the 2-axis IPP. Commanding the IPP to perform scans and mosaics is tricky, and if we needed a simulation run by the MOC to visualize the output, it would lead to many unnecessary iterations. That's were the Science Encounter Simulation Software (SESS) [5] has facilitated the reviews for the SOC team. SESS was developed by the science team to model the encounter sequences and assess whether science requirements are met. It outputs data that can be plotted as resolution maps and coverage maps, helping us determine early whether science requirements are met. SESS takes into consideration various sources of errors like navigation knowledge uncertainties, spacecraft and IPP pointing uncertainties, spacecraft jitter, instrument alignment uncertainties, etc.

The SOC has benefited from this software because it models the spacecraft and IPP attitude, and outputs attitude data in both SPICE and STK format, allowing us to produce the full set of review products including STK graphics, movies and reports. Having access to this attitude data before delivering a sequence to the MOC has made the SOC sequence development significantly more efficient and has reduced iterations with the MOC.

8 Improvements to be made for future flybys

While many improvements were made in the design of Lucy SOC software and processes since the New Horizons mission, there is still room for further improvement.

Tool updates are desired to further automate STK graphics, specifically for producing movies. Still, JPEGs are not sufficient to capture the fast-changing geometry around the time of closest approach. The movies are manually produced with STK, but it is tedious. When we have many versions of a sequence and many different simulations for each version, the movies end up not being produced every time, and only as needed or when requested.

When designing Ralph scans, the science sequencer must select scan mirror start and stop position taking into account the scan run up and all sources of uncertainties, including navigation, pointing, and scan mirror uncertainties. The nav/pointing uncertainty guidelines are such that they are a function of target size, and whether we're currently using state estimation or onboard knowledge. A separate script was written to facilitate the calculation of the scan mirror start/stop position, which has helped, but it means that the data end up in a spreadsheet and the numbers are manually transferred into the block call for each individual acquisition. It would be possible and probably a good idea to have this calculation be done inside TPFG, while also allowing the sequencer to override the calculated values as needed.

Many other desired TPFG updates are being tracked, including adding more flexibility to bulk updates, and introducing an 'undo' button. Not having an option to undo an action at the interface is proving to be a shortcoming of the software.

In addition to commanding the instrument acquisitions for a flyby, it is also the responsibility of the SOC to build what we call the "retrieve" commanding, which pulls the data off the instrument internal recorders and transfers them to the spacecraft partition for downlink. The retrieve commanding has been partially automated but the script needs some work, and we currently don't have efficient ways to review the retrieve commanding without very tedious manual parsing of command timelines. A plan is in place to incorporate the parsing of retrieve commanding into DUIT for visualization in AILT.

Conclusions

The Lucy SOC has designed and developed the set of tools and processes needed to build the science encounter commands loads to ensure that we meet science requirements, while also satisfying spacecraft and instrument constraints. The tools facilitate the initial building of the command load, while also automating much of the review products creation. The TPFG software was designed to allow the science team to build the initial command loads and this process has worked well. The development of the Donaldjohanson encounter load exercised all these tools and processes and has helped us be prepared for the upcoming Trojan asteroid flyby. We're anxiously awaiting the Donaldjohanson encounter day, and upcoming Trojan asteroid flybys over the next few years!

Acknowledgements

We would like to thank the entire Lucy team for all the work that went into the developing the Donaldjohanson command loads, and for all the support the SOC has received from various teams and subsystem for the last few years. The Lockheed MOC work very closely with the SOC every step of the way, from the initial planning for encounters and calibrations to the data downlink transfers. Operating the IPP and understanding the intricacies of the terminal tracking system has been a work in progress and the Guidance Navigation & Control team has been very patient with answering our frequent questions. The science, instrument, and navigation teams have a lot of overlapping members from New Horizons and we're excited for the opportunity to work together again with this incredible team.

We could not have done all this without the help from Big Head Endian (BHE) who developed the DUIT tool and several other software tools on the downlink and data processing side.

Last but not least, we would like to thank NASA and our Principal Investigator Hal Levison for the opportunity to work on this incredible mission!

References

[1] Brian Keeney, Michael Vincent, Jon Pineau, Emma Birath, Zach Talpas, David Kaufmann, Caden Gobat, Kate Crombie, Joel Parker, John Spencer, and the Lucy SOC. Lucy's Encounter with Dinkinesh. Abstract #540, 18th International Conference on Space Operations, Montreal, Canada, 26 – 30 May 2025.

[2] Harold F. Levison, Simone Marchi, Keith S. Noll, John R. Spencer, Thomas S. Statler, James F. Bell III, Edward B. Bierhaus, Richard Binzel, William F. Bottke, Daniel Britt, Michael E. Brown, Marc W. Buie, Philip R. Christensen, Neil Dello Russo, Joshua P. Emery, William M. Grundy, Matthias Hahn, Victoria E. Hamilton, Carly Howett, Hannah Kaplan, Katherine Kretke, Tod R. Lauer, Claudia Manzoni, Raphael Marschall, Audrey C. Martin, Brian H. May, Stefano Mottola, Catherine B. Olkin, Martin Pätzold, Joel Wm. Parker, Simon Porter, Frank Preusker, Silvia Protopapa, Dennis C. Reuter, Stuart J. Robbins, Julien Salmon, Amy A. Simon, S. Alan Stern, Jessica M. Sunshine, Ian Wong, Harold A. Weaver, Coralie Adam, Shanti Ancheta, John Andrews, Saadat Anwar, Olivier S. Barnouin, Matthew Beasley, Kevin E. Berry, Emma Birath, Bryce Bolin, Mark Booco, Rich Burns, Pam Campbell, Russell Carpenter, Katherine Crombie, Mark Effertz, Emily Eifert, Caroline Ellis, Preston Faiks, Joel Fischetti, Paul Fleming, Kristen Francis, Ray Franco, Sandy Freund, Claire Gallagher, Jeroen Geeraert, Caden Gobat, Donovan Gorgas, Chris Granat, Sheila Gray, Patrick Haas, Ann Harch, Katie Hegedus, Chris Isabelle, Bill Jackson, Taylor Jacob, Sherry Jennings, David Kaufmann, Brian A. Keeney, Thomas Kennedy, Karl Lauffer, Erik Lessac-Chenen, Rob Leonard, Andrew Levine, Allen Lunsford, Tim Martin, Jim McAdams, Greg Mehall, Trevor Merkley, Graham Miller, Matthew Montanaro, Anna Montgomery, Graham Murphy, Maxwell Myers, Derek S. Nelson, Adriana Ocampo, Ryan Olds, John Y. Pelgrift, Trevor Perkins, Jon Pineau, Devin Poland, Vaishnavi Ramanan, Debi Rose, Eric Sahr, Owen Short, Ishita Solanki, Dale Stanbridge, Brian Sutter, Zachary Talpas, Howard Taylor, Bo Treiu, Nate Vermeer, Michael Vincent, Mike Wallace, Gerald Weigle, Daniel R. Wibben, Zach Wiens, John P. Wilson, and Yifan Zhao. A contact binary satellite of the asteroid (152830) Dinkinesh. Nature, Volume 629, Issue 8014, pp. 1015-1020, 2024 May.

[3] Catherine B. Olkin , Harold F. Levison, Michael Vincent, Keith S. Noll, John Andrews, Sheila Gray, Phil Good, Simone Marchi, Phil Christensen, Dennis Reuter, Harold Weaver, Martin Pätzold, James F. Bell III, Victoria E. Hamilton, Neil Dello Russo, Amy Simon, Matt Beasley, Will Grundy, Carly Howett, John Spencer, Michael Ravine, and Michael Caplinger. Lucy Mission to the Trojan Asteroids: Instrumentation and Encounter Concept of Operations. Planetary Science Journal, 2:172, 2021 October.

[4] Philip Good, Preston Faiks, William J. Pisano. Terminal Tracking for the Lucy Trojan Asteroid Mission. Proceedings of the 2022 AAS G&C Conference, Breckenridge, Colorado.

[5] Julien Salmon, Harold F. Levison, David E. Kaufmann, Catherine Olkin, Michael Vincent, Simulating the Encounters of NASA's Lucy Spacecraft with its Target Trojan Asteroids. Proceedings from 2021 IEEE Aerospace Conference.