(Preprint) AAS 23-247

LUCY ORBIT DETERMINATION PERFORMANCE FROM LAUNCH THROUGH EGA-1

Jeroen L. Geeraert[*], Joel T. Fischetti[†], Dale R. Stanbridge[‡], Coralie D. Adam[§], Jim V. McAdams[¶], Kevin Berry[‖], Jason M. Leonard[**], Daniel Wibben[**], John Y. Pelgrift[**], Michael J. Salinas[**], and Chris G. Bryan[**]

Lucy is a 12-year long NASA Discovery-class mission which launched on October 16, 2021 and is currently on its way to the Jupiter-Trojan asteroids at the L4 and L5 Lagrange points. On its journey to the Trojan asteroids, Lucy will also fly by two main belt asteroids, and perform 3 Earth fly bys. This paper summarizes primarily the Orbit Determination (OD) aspect of the first year of the mission from launch through the first Earth fly by (EGA-1). Some challenges were encountered for OD as part of the +Y solar array not fully deploying, but these were resolved within the first year of flight. The high quality radio-metric data from the Deep Space Network including 2- and 3-way Doppler, sequential 2-way ranging, complemented by delta differential one-way ranging (ΔDOR) has enabled the OD team to characterize the Solar Radiation Pressure force, resolve desaturation maneuvers, generate both maneuver reconstructions and accurate long-term predicted trajectories. This paper discusses the filter setup and strategies implemented, as well as the OD performance from launch, through cruise, and including EGA-1.

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 primary targets for Lucy are the Jupiter-Trojan asteroids located at the L4 and L5 Lagrange points.[1] Between August 2027 and November 2028 Lucy will encounter and fly by 4 asteroids in the L4 region, and in March 2033, after the final Earth fly by in 2030, Lucy will encounter a final binary asteroid in the L5 region.[2] On its way to the Jupiter-Trojan asteroids, there will be two encounters with main belt asteroids, the first in November of 2023 is Dinkinesh, and the second in April of 2025 of Donaldjohanson.

[*] OD Team Lead, KinetX, Inc., Space Navigation and Flight Dynamics, 21 W. Easy St., Ste 108, Simi Valley, CA 93065, USA.
[†] OD Team Member, KinetX, Inc., Space Navigation and Flight Dynamics, 21 W. Easy St., Ste 108, Simi Valley, CA 93065, USA.
[‡] Nav Team Chief, KinetX, Inc., Space Navigation and Flight Dynamics, 21 W. Easy St., Ste 108, Simi Valley, CA 93065, USA.
[§] Deputy Nav Team Chief, KinetX, Inc., Space Navigation and Flight Dynamics, 21 W. Easy St., Ste 108, Simi Valley, CA 93065, USA.
[¶] Maneuver Team Lead, KinetX, Inc., Space Navigation and Flight Dynamics, 21 W. Easy St., Ste 108, Simi Valley, CA 93065, USA.
[‖] Flight Dynamics Lead, NASA/GSFC Navigation and Mission Design Branch, 8800 Greenbelt Rd, Greenbelt, MD 20771, USA.
[**] Launch OD Team Member, KinetX, Inc., Space Navigation and Flight Dynamics, 21 W. Easy St., Ste 108, Simi Valley, CA 93065, USA.

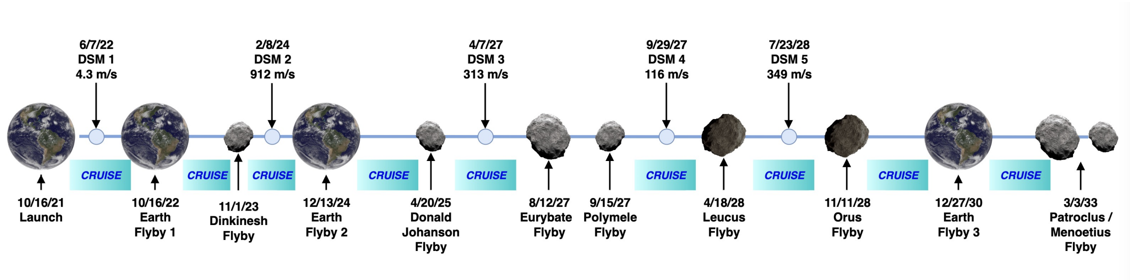


Figure 1: Lucy Mission Timeline

Figure 1 illustrates the mission timeline of all the asteroid encounters and all three Earth fly bys in addition to the deterministic Deep Space Maneuvers (DSMs). The Lucy mission is still in its early stages with this paper covering the first year of the 12-year planned primary mission. The main planned events in the first year were launch, DSM-1, and the first of three Earth Gravity Assists (EGAs). EGA-1 was designed into the trajectory as a placeholder in case the 2021 launch window was missed. This is a common way to include schedule margin, if the first launch window closes without a successful launch. The backup window one year later can then put the spacecraft directly on the post-EGA-1 trajectory. EGA-1 primarily increased the heliocentric orbit semi-major axis, putting Lucy on a 2:1 orbital resonance with Earth. However, because Lucy successfully launched in the first available launch window, that provided time for the navigation and spacecraft teams to learn the unique characteristics of flying the Lucy Spacecraft.

Shortly after launch, the spacecraft team discovered that the +Y solar array did not fully deploy and latch. Analysis suggested that the panel was over 98% deployed, and starting on May 9, 2022, the first of a series of Re-Deployment Attempts (RDAs) were performed to try and latch the solar array. As of this paper's writing, the 3rd and last series of attempts ended on December 13, 2022, the project decided to temporarily suspend further attempts since no measurable progress on latching the solar array was made. There was also no significant power loss or risk of damage to the array if flown as-is for the remainder of the mission. Challenges were presented to the Navigation team as a result of the partially deployed solar array and the RDAs. On the Orbit Determination (OD) side, those challenges consisted of modeling the Solar Radiation Pressure (SRP) correctly with a changing geometry of the +Y solar array, as well as the indirect effect of increased momentum accumulation and consequently an increased number of executed desaturation maneuvers (desats).

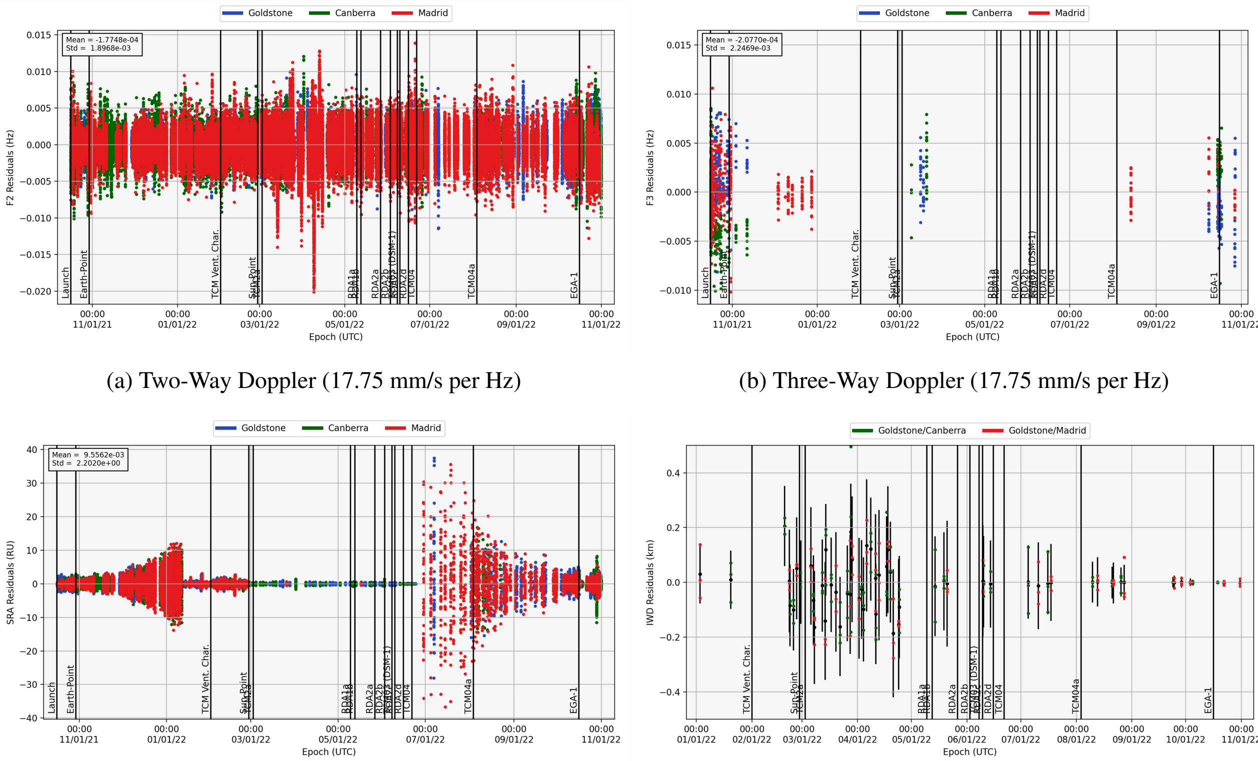
In this paper the OD models, tracking data, and filter strategies are discussed, in addition to the performance and reconstruction of launch, executed maneuvers, and the EGA-1 fly by. We also discuss the challenges of the solar array deployment issue as well the desat frequency and its observability. The first year of the Lucy mission was a success on all fronts including the OD and navigation overall. At the time of this writing, the Lucy team is in the midst of preparing for the first asteroid encounter of Dinkinesh this coming Fall.

LUCY ORBIT DETERMINATION OVERVIEW

In this section we discuss the background necessary for the radio-metric tracking data used, the dynamical models, as well as the filter setup and strategies employed.

Radio-Metric Tracking Data

For the first year of the Lucy mission, tracking data were limited to X-band radiometric measurements, including two-way and three-way Doppler, sequential two-way ranging (SRA), and Delta Differential One-way Ranging (ΔDOR). Optical navigation will not be utilized until the first encounter with Dinkinesh in the Fall of 2023. The tracking data comes from the Deep Space Network (DSN) with its three complexes, at Goldstone in California, Madrid in Spain, and Canberra in Australia. The nominal 1σ DSN data weights are 0.1 mm/s (0.0055 Hz) for 60 s integrated Doppler, 3 m (21 Range Units) for Range, and 0.06 ns for the ΔDOR measurements.[3] Although the actual data weights implemented were based on the noise of the tracking pass, the pass was de-weighted to 3 times the RMS noise of the pass to account for the timescales of the turbulent



(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

Figure 2: Radio-Metric Tracking Residuals

processes in the Earth's atmosphere.[4,5] Table 1 shows the nominal weightings for each measurement type as well as an averaged value over the year based on the weight-by-pass strategy.

Table 1: X-band Tracking Data Weightings Strategy

Data Type	DSN Req. 1-σ	Unc. in Filter 1-σ	Notes
X-band Two-way Doppler	0.1 mm/s	0.034 mm/s (avg over 1st year)	3× RMS noise of pass
X-band Three-way Doppler	0.1 mm/s	0.04 mm/s (avg over 1st year)	3× RMS noise of pass
X-band SRA	3 m	0.31 m (avg over 1st year)	3× RMS noise of pass
ΔDOR	0.06 ns	0.06 ns	-

As demonstrated in column 3 of Table 1, the DSN noise performance of the Doppler and Ranging passes were significantly lower than the DSN requirement values. This is further supported by the residuals shown in Figure 2. The noise on the Doppler residuals stayed fairly constant throughout the first year of operations, however the ranging noise was more dependent on the Earth-probe distance as well as the spacecraft antenna used for tracking. Lucys primary on-board antenna is the High Gain Antenna (HGA), though it is also equipped with a Medium Gain Antenna (MGA) and a Low Gain Antenna (LGA). The first several months after launch were on the LGA and MGA because the HGA was too sensitive to be used at a close Earth range. The noise on the range steadily grew until the communication antenna was switched to the HGA on 12 January, 2022 when the noise dropped to less than 1 RU. After TCM-04 (Trajectory Correction Maneuver), on 24 June, 2022 the communications antenna was switched back to the LGA and stayed there until after EGA-1 due to the Sun-Probe-Earth (SPE) angle geometry.

Dynamical Models

The Lucy spacecraft, built by Lockheed Martin (LM) in Denver, CO, is shown in Figure 4 and had a launch mass of 1500.4 kg. Lucy has large solar arrays in order to have sufficient power to operate at a Sun-Jupiter distance of more than 5 AU. With a solar array diameter of 7.3 m, and a combined surface area of more than 80 m^2, SRP is the largest non-conservative force acting on the spacecraft with an acceleration on the order of 1.E-10 km/s^2 during the first year of the mission.

The Lucy SRP model initially comprised of a 6-plate model with a single plate representing each of the 6 spacecraft body directions. This was then updated to a 10-plate model so that unique optical properties could be assigned to each of the plates, distinguishing the solar array properties from the bus for example. Finally, a 10×10 spherical harmonics model was implemented to accurately capture the varying SRP acceleration due to the complex structure of the Lucy spacecraft. These accelerations were generated from Ray-Tracing an OBJ model of Lucy at a resolution of 2° in solar latitude and longitude similar to what was done on the OSIRIS-REx asteroid sample return mission.[6] The spacecraft OBJ model was resolved to three unique optical properties defined by the bus covered in Germanium Kapton, the front of the solar array covered in solar cells and the back of the solar array. The diffuse coefficient in Table 2 includes the added term, $k(1-r)$ where k is the emissivity and r is the reflectivity, to account for thermal re-radiation. Therefore both the SRP and thermal re-radiation accelerations are wrapped up in a single model.

Table 2: Optical Properties for the Lucy Spacecraft SRP and Thermal Re-radiation Models

	Specular Coefficient	**Diffuse Coefficient**
Bus	0.336	0.139
Solar Array (Front)	0.160	0.160
Solar Array (Back)	0.0	0.560

The accelerations produced by the SRP/Thermal model are shown in Figure 3, with accelerations in the spacecraft body X, Y, and Z directions. A solar longitude and latitude of 0° signifies a Sun vector along the +X axis, and perpendicular to the solar arrays which maximizes the acceleration - dark blue. The Sun vector should never be aligned with the -X axis, even though that is still shown as well - dark red.

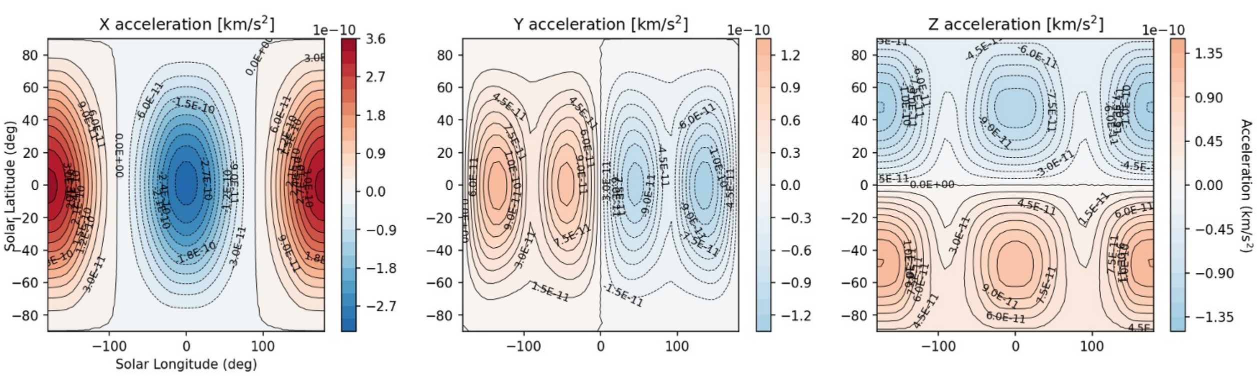


Figure 3: Solar Radiation and Thermal Accelerations imparted on Lucy given the Solar Longitude and Latitude Angles

In addition to the SRP/Thermal model, other modeled non-conservative forces are the four finite TCMs executed between launch and EGA-1, in addition to desats which are modeled as instantaneous position and velocity deltas. There were also tests such as the TCM thruster characterization which were modeled with instantaneous burns. Finally, because of the low altitude EGA-1 fly by, a scale height driven exponential model for atmospheric drag was used.

The conservative gravitational forces modeled include all the planets in addition to Pluto and use the DE430 planetary ephemeris.[7] The Earth gravity field was included up to degree and order 50 from the EGM2008 gravity field model, and the Lunar gravity field was included up to degree and order 20 truncated from the LP150Q field. The Dinkinesh ephemeris and GM are also included but the effect of the GM is negligible until the Dinkinesh encounter date, which is beyond the timeline of this paper. Three of the small bodies that Lucy is visiting including Dinkinesh and Donaldjohanson are referenced to the DE441 planetary ephemeris while the other small body ephemerides are still relative to DE431. There is a significant shift in the solar system barycenter (SSBC) between DE430 and DE440 which is primarily due to added KBOs.[8] Care must be taken when incorporating small bodies referenced to a different planetary ephemeris, but as long as the integration center is set to the Sun rather than the SSBC, the results will be consistent.

Filter Setup and Strategies

The launch filter setup is shown in Table 3. This is a simplified setup because launch is generally dominated by large accelerations such as outgassing, and there is no prior empirical information available on the spacecraft dynamics or state. Prior to launch an initial state was provided by United Launch Alliance (ULA) for the Trajectory Injection Point (TIP) state along with a corresponding 6×6 correlated Injection Covariance Matrix (ICM). For Lucy, TIP was approximately 20 minutes after the 2nd stage main engine cutoff time. All of the launch OD setups started with the ICM state, however various alternate state uncertainties were employed. Some cases used the ICM, with other cases dropping the correlations to keep the solution less constrained, and still others employed a completely open a-priori uncertainty of 500 km in position and 300 m/s in each of the velocity components. Approximately 45 minutes after spacecraft separation from the second stage, ULA delivered the Orbit Parameter Messages (OPM), containing an updated injection state and covariance, to the Navigation team. Additional solutions were then produced with variations on the OPM state and its covariance.

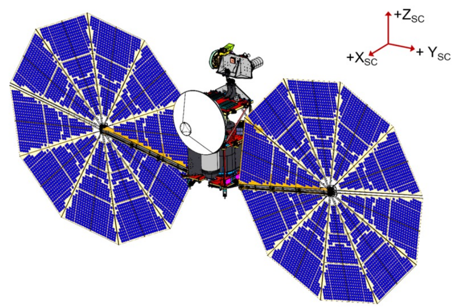


Figure 4: Lucy Spacecraft

Table 3: Launch Orbit Determination Filter Configuration

Parameter	Type	A-priori 1-σ	Notes
Epoch State	Estimated	6×6 ICM Covariance 6×6 OPM Covariance 500 km and 300 m/s	Epoch state from ICM or OPM with multiple a-priori strategies executed
SRP Scale Factor	Estimated	0.01	-
Outgassing	Estimated	1.0E-11 km/s^2	Per axis exponential decay
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	-

The purpose of the launch OD setup was to ensure that Canberra had initial acquisition, and then afterward that Madrid could acquire for the second pass. Because of the lack of tracking data early on, it is best to simplify the setup so that the filter does not effectively have an under-determined system with too many solve-for parameters and not enough data. One of the few parameters estimated was an exponential decay acceleration covering the first several days as new sides of the spacecraft were exposed to the Sun resulting in outgassing or boil-off from any moisture that was present on the surface. The SRP scale factor was effectively left at the a-priori value of 1.0, and while there was room for it to move with a 1% apriori sigma, it did not change significantly over the launch timespan. Within the first several days after launch the OD setup was re-configured to the setup shown in Table 4.

In many of the arcs during cruise the epoch state and covariance were derived from the previous arc, usually with the state uncertainties inflated by a factor of three, and the correlations dropped. Once the team realized that the +Y solar array was not latched, the SRP scale factor was updated to a white noise stochastic parameter batched over a timespan between solar array RDAs. This was necessary to account for the changing SRP acceleration before and after an RDA over a single arc. Each RDA slightly changed the solar array geometry and gore angles which affected the estimated SRP scale factor. Prior to the RDAs the estimated scale factor was in the vicinity of -2%. After RDA1a on May 9, 2022 the scale factor changed to -0.5%, and then to +0.2% after RDA1b. RDA2a-c had an estimated SRP scale factor around +1% but the uncertainty was nearly 1% because of the short amount of time between these RDAs. The final RDA (RDAd) resulted in a scale factor of close to +2% with a small uncertainty. In summary, the RDAs caused an increased trend in SRP suggesting that the solar array become more deployed despite not being fully latched. The arcs were on the order of several months long and even covered up to 6 months or more at a time. When the SRP model was changed to the high fidelity spherical harmonics model, the scale factor would primarily absorb errors in the optical properties that were used during ray-tracing and other minor errors such as a different IPP arrangement.

Table 4: Cruise and EGA-1 Orbit Determination Filter Configuration

Parameter	Type	A-priori 1-σ	Notes
Epoch State	Estimated	3$\times$ previous arc sigma	State and uncertainty derived from previous arc
SRP Scale Factor	Estimated	0.03	White noise stochastic model, batch start at each RDA
Finite Burns (ΔV, RA, DEC)	Estimated	30 mm/s + 4% of $\|\Delta v\|$	TCM thrusters only $<$10 m/s
Desats	Estimated	0.4 mm/s	Per axis
Per-Pass Range Biases	Estimated	4 m	White noise stochastic model, batch start at range pass
Accelerations	Estimated	1.0E-12 km/s^2	Per axis, white noise stochastic model with 3 day batches
Future Desats	Considered	0.4 mm/s	Per axis
Future Accelerations	Considered	3.0E-12 km/s^2	Per axis, white noise stochastic model with 3 day batches
Earth Ephemeris	Considered	12$\times$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	-

For each of the executed finite burns, the ΔV, RA, and DEC parameters were estimated and the a-priori uncertainty values for each of those parameters varied depending on the size of the burn. In the first year of operations, these finite burns all had the same execution error model because they were all on TCM thrusters and were less than 10 m/s in ΔV. Other parameters such as the thrust profile, start of burn, or burn duration were not estimated because the communication link could not be closed during the burn attitudes so there was no tracking data for the burn duration. Per-Pass Range biases were also estimated with a 1-σ uncertainty of 4 m, these biases are to account for variations in the Troposphere and Ionosphere since those parameters are only considered instead of estimated. Any path delays due to thermal noise would also be absorbed by this estimated parameter.

The baseline desat a-priori σ is 0.4 mm/s, with an a-priori value of 0.0 mm/s. However, for a significant portion of first year operations the a-priori desat σ was purposefully set to 0.01 mm/s with a predicted or reconstructed desat value. The reason for this was a result of the unlatched solar array which caused significant momentum accumulation from the uneven torque applied on the un-symmetric solar array geometries. Therefore, the desats occurred on a near-daily basis rather than the pre-launch expected cadence of 15 days. While nominally the Reaction Control System (RCS) thrusters, used for desats, are balanced and would cancel completely that is rarely the case in reality, resulting in a small imparted ΔV with each desat. These ΔVs were often unobservable since they would usually occur between tracking passes. Furthermore, multiple desats often occurred between the tracking passes, making it difficult to separate them. During these early stages of the mission, the SRP model for Lucy was based on a 10-plate model which had its limitations and error sources. Solving for the SRP scale factor was a challenge with daily unobservable desats, as the two parameters would constantly be conflated. Often, part of the SRP acceleration would be absorbed by the estimated desats, which resulted in a secular acceleration not accounted for in the predicted trajectory. During the lead-up to EGA-1, the desats were effectively fixed to the reconstructed values provided by the GNC team at Lockheed Martin (LM) so that the OD team could better estimate the SRP acceleration. This strategy resulted in an accurately targeted EGA-1 with successive near-concentric B-planes shown in subsection Launch Reconstruction. Due to the challenge of SRP and desat conflation the OD team requested the Spacecraft team to forgo executing any desats for some period of time in order to get a better estimate of the SRP. The spacecraft team came up with the Desat Avoidance Maneuver (DAM) where Lucy would be flipped 180° about the spacecraft X-axis to counteract the previous momentum accumulation. The test was conducted from August 25, 2022 to September 2, 2022, and while useful, it was not quite long enough to conclusively validate and estimate the SRP model. Indifferent to the reconstructed desat a-priori σ used, the future desats were modeled at the baseline value of 0.4 mm/s.

The last set of estimated parameters in a normal cruise and EGA-1 OD configuration are random unmodeled accelerations, which use a white noise stochastic model with 3-day batches in each axis. These had a-priori values of 0.0 km/s^2 with 1.0E-12 km/s^2 1-σ a-priori uncertainty. The uncertainty value was chosen to encompass the random accelerations seen during cruise, in general the estimated accelerations were well within the 1-σ bound. For conservativeness however, future accelerations are modeled at the 3.0E-12 km/s^2 1-σ uncertainty level.

Finally, all the considered parameters except for future desats and accelerations are the same between the launch and cruise/EGA-1 OD setups.

ORBIT DETERMINATION PERFORMANCE

This section discusses the OD performance through the various stages of flight including the launch, cruise, and EGA-1 fly by.

Launch Reconstruction

The Lucy spacecraft successfully launched in the first available launch window at the first available time on October 16, 2021 at 9:34 UTC. The launch period spanned from October 16 to November 7, with launch opportunities occurring every 5 minutes within the 65-75 minute daily window. The pre-launch M40 (M40 denotes minus 40 minutes relative to the minimum-ΔV trajectory on a given launch date) nominal trajectory for October 16 was used as the reference based on the expected launch time. The launch was nominal and separation (SEP) between the upper stage of the launch vehicle and the spacecraft occurred at 10:32 UTC. Six and a half minutes later marked the start of the solar array deployment, with the TIP epoch defined immediately afterward. At 11:28 UTC, Lucy was in communication attitude and on reaction wheels, this was also the latest expected initial acquisition time. Actual carrier lock with Canberra DSS-34 and DSS-36 stations occurred at 10:40 UTC with two-way data starting at 11:29 UTC. Ranging was turned on at SEP+90 minutes or 12:02 UTC.

Table 5: Launch Injection Estimates

	Pre-Launch Predict		**OPM**		**TDRSS**		**OD***	
	Value	Sigma	Value	Sigma	Value	Sigma	Value	Sigma
C3 (km^2/s^2)	28.635	0.05	28.630	0.093	28.628	0.15	28.631	5.189E-06
RLA (deg)	17.797	0.06	17.800	0.041	17.802	0.073	17.798	9.502E-04
DLA (deg)	6.275	0.09	6.276	0.018	6.278	0.038	6.280	2.461E-03

*OD001 with a tracking data cutoff of 16 October, 2021 15:40:27 UTC (~4 hours of tracking)

Table 5 lists the pre-launch hyperbolic injection predicts based on the M40 nominal trajectory and the ULA 1-σ requirements in terms of C3 (twice the specific per unit mass orbital energy), RLA (Right Ascension) and DLA (Declination). Shortly after launch, ULA delivered the OPM which was consistent with the nominal pre-launch trajectory. Tracking and Data Relay Satellite System (TDRSS) further validated these results, and finally when the first OD (OD001) was delivered, consistent injection estimates to the prior values were obtained as well. The launch injection performance, when viewed in the plane of sky, from the initial acquisition station (DSS-36) at Canberra is illustrated in Figure 5(a). The OPM from ULA, the Goddard Flight Dynamics Facility (FDF) solution, and KinetX's OD001 solution are all grouped together well within the 1-σ ellipse. The Lucy location in the plane-of-sky is not within the beamwidth of DSS-36 however, so a scan still had to be performed in order to acquire the signal. Prior to launch the DSN had expressed a desire to avoid the use of an Acquisition Aid which has a much wider half-power beamwidth than their 34 m BWG antennas. OD001 was delivered to the DSN 2 hours prior to Madrid acquisition on DSS-54 and DSS-56. Figure 5(b) shows that the predicted spacecraft location as viewed from the Madrid complex which is well within the antenna's beamwidth centered on the pre-launch reference trajectory, demonstrating that a pointing offset would not be needed.

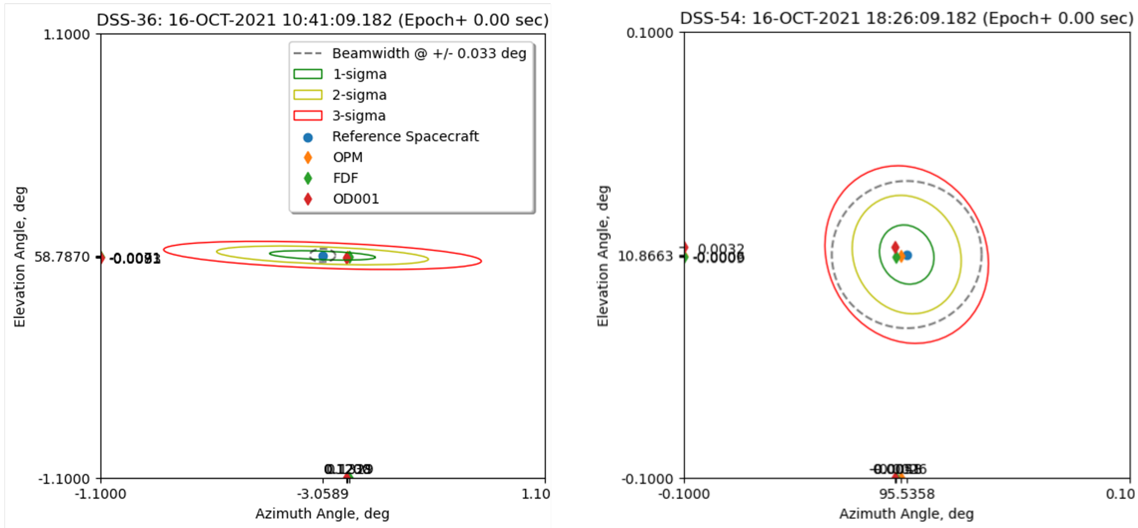
After the Madrid handover was successfully completed, OD continued incorporating new tracking data into the OD002 solution which was then uploaded to SPS for the Goldstone handover to DSS-24, and DSS-25 on 17 October, 2021 04:20 UTC. One more OD solution, OD003, was generated that day to generate a longer term trajectory and lighttime file for DSN tracking. OD003 was stable and used for the next 2.5 weeks which signifies the transition to the cruise phase.

Cruise Maneuver Reconstructions

Due to the successful launch injection onto the planned trajectory the two clean up maneuvers, following launch on L + 30 days (TCM-01) and L + 60 days (TCM-02) targeting TCM-03 (DSM-1), were canceled.

TCM-02a The first maneuver targeting DSM-1, called TCM-02a occurred on L + 137 days, on 2 March, 2022 and executed on TCM thrusters with a ΔV of 1.251 m/s. OD008 was used to support the final design of the TCM-02a maneuver with a DCO of 13 February, 2022. The design and reconstructed ΔV magnitude and direction values for TCM-02a are shown in Table 6 with the largest error in the declination component of the pointing.

TCM-03 (DSM-1) The first deterministic maneuver of the mission was DSM-1, occurring on June 7, 2022 with an EGA-1 biased target. This maneuver had a biased EGA aimpoint to ensure $<$1% probability of Earth



(a) Initial Acquisition at Canberra (DSS-36)

(b) Predicted Madrid Handover (DSS-54)

Figure 5: DSN Azimuth/Elevation View

impact if no other maneuvers were executed after DSM-1 up to EGA-1. This maneuver executed on the TCM thrusters with a ΔV of 4.206 m/s. OD013 with a DCO of 27 May, 2022 was utilized for the final design of DSM-1. The reconstruct values in Table 6 show that the maneuver executed significantly better than the a-priori σs might suggest. OD014 through OD016 were used to reconstruct the maneuver and Figure 6 shows the OD015 and OD016 solutions of where Lucy ended up in the Earth's B-plane with their time of closest approach (TCA) uncertainties.

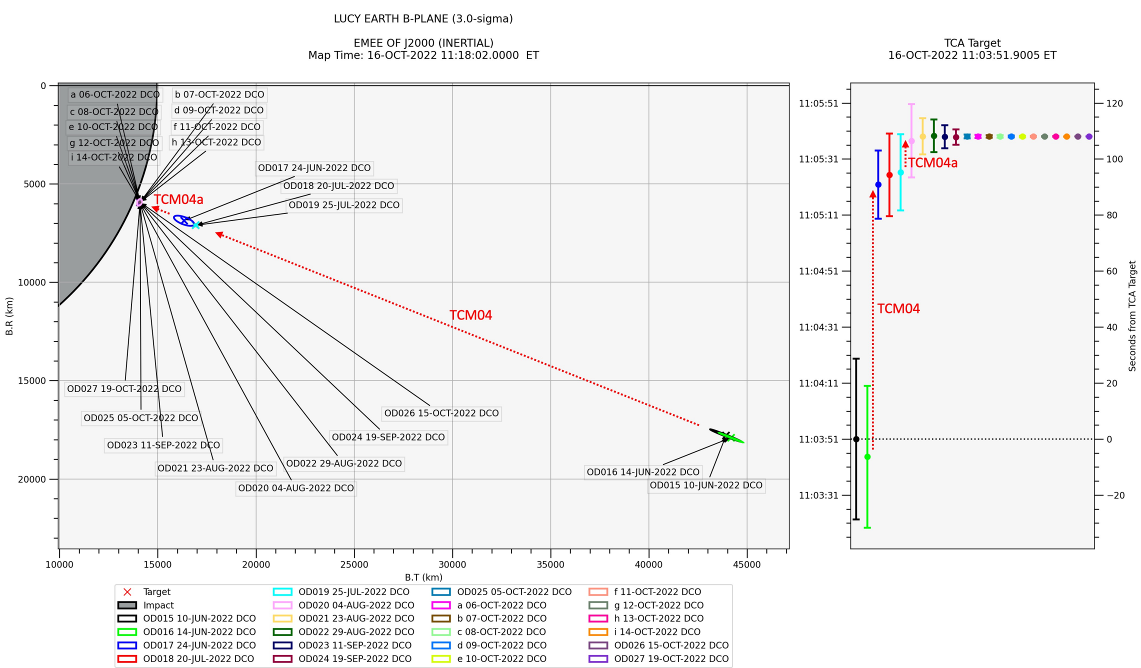


Figure 6: EGA-1 B-plane Progression OD015 - OD027

TCM-04 Fourteen days after DSM-1 was a statistical maneuver placeholder for TMC04. This maneuver executed on 21 June 2022 on TCM thrusters with a ΔV of 1.531 m/s. This maneuver, just like DSM-1, targeted a biased EGA-1 aim point. The biased target values were 15926.178 km in B·T, 6708.750 km in B·R, with an epoch of 16 October, 2022 11:04:22.278 UTC. The TCM-04 maneuver shifted the B-plane intercept point significantly closer to the Earth and also delayed the Time of Close Approach (TCA) as illustrated in Figure 6 with OD017 through OD019 used to reconstruct the maneuver. OD016 was used for the final Design of TCM-04 and had a DCO of 14 June, 2022. This was another successfully executed maneuver with the reconstruct values listed in Table 6.

TCM-04a The final executed maneuver before EGA-1 was TCM-04a on August 3, 2022 which removed the EGA-1 bias from the previously executed maneuvers. This maneuver was once again executed using the TCM thrusters and had a ΔV of 0.415 m/s. The EGA-1 target values were 14086.887 km in B·T, 5933.946 km in B·R, with an epoch of 16 October, 2022 11:04:26.564 UTC. The shift from the biased EGA-1 aim point to the final non-biased aim point is also shown in Figure 6. OD019 was used for the final design of this maneuver with a DCO of 25 July, 2022. This was another well executed maneuver as demonstrated by the small differences between the estimated and design values.

Table 6: Executed Maneuver Reconstructions

Maneuver	Epoch (UTC)	Parameter	Design	Estimated	Smoothed σ	A-priori σ
TCM-02a	2-Mar-2022 17:00:00	ΔV (m/s)	1.250	1.251	0.000381	0.010671
		RA (deg)	55.828	55.810	0.04511	1.07165
		DEC (deg)	5.576	5.363	0.06006	1.06658
TCM-03	07-Jun-2022 17:00:00	ΔV (m/s)	4.201	4.206	0.001777	0.028794
		RA (deg)	63.920	63.723	0.009001	0.84602
		DEC (deg)	21.784	21.749	0.01815	0.78560
TCM-04	21-Jun-2022 17:00:00	ΔV (m/s)	1.527	1.531	0.000650	0.012170
		RA (deg)	80.710	80.225	0.0118	1.08089
		DEC (deg)	23.136	23.158	0.04434	0.99395
TCM-04a	03-Aug-2022 17:00:00	ΔV (m/s)	0.415	0.415	0.000839	0.00721
		RA (deg)	112.526	112.796	0.046308	2.03391
		DEC (deg)	23.089	23.076	0.09808	1.87098

The four maneuvers listed in Table 6 are the only maneuvers executed in the first 13 months of operations, despite up to 10 having been planned. The following section goes over the EGA-1 operations for OD, but none of the maneuvers around EGA-1 were executed since the TCM-04a maneuver hit the target and the predicted OD remained stable throughout approach.

EGA-1 Reconstruction

Two targeting maneuvers prior to EGA-1, TCM-05 and TCM-06 were put in as placeholders at EGA - 30 days and EGA - 10 days. Two clean-up maneuvers after EGA-1, TCM-07 and TCM-08 were also placed on the EGA encounter timeline at EGA + 17 days and EGA + 37 days, respectively. This EGA maneuver schedule is graphically shown in Figure 7. However, none of these maneuvers were executed because Lucy came close to its EGA target, requiring no additional correction. The TCM-06a/b maneuvers shown are not targeting maneuvers, but rather collision avoidance maneuvers had it become necessary.

The Lucy trajectory has a targeted perigee altitude of 352 km which is well within low Earth orbit where the spacecraft and space junk population is high, and with a close approach speed of 12.1 km/s a collision would be mission-ending. At EGA - 10 days, daily OD solutions (OD025a-h) were generated and sent to the Conjunction Assessment and Risk Analysis (CARA) group at NASA. They evaluated the potential probability of a collision and sent out reports twice daily using our latest OD. The TCM-06a maneuver was pre-canned

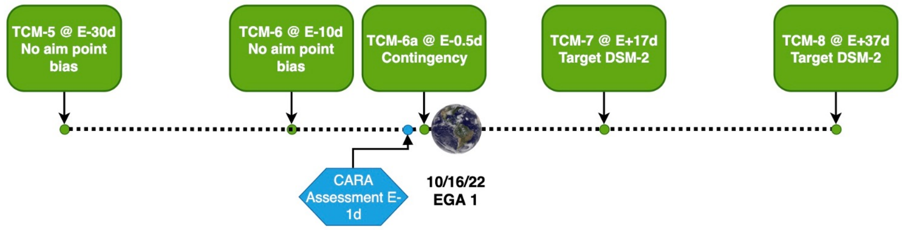
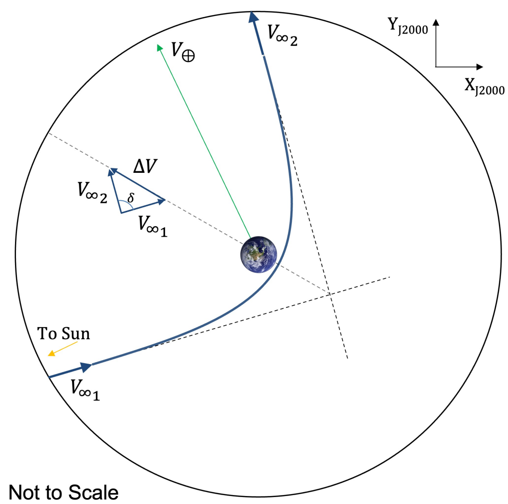


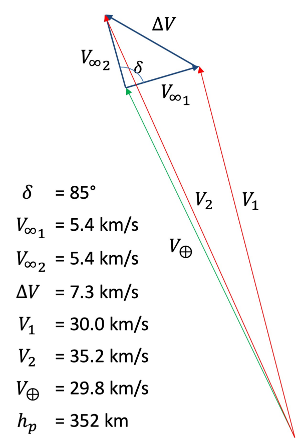
Figure 7: EGA-1 Timeline

and changes the close approach time by 2 seconds with a ΔV of 0.285 m/s, the TCM-06b maneuver was also pre-canned, and changes the close approach time by 4 seconds with a ΔV of 0.575 m/s. Changes in the close approach time of a mere few seconds can change the spacecraft position by several tens of kms which is sufficient for collision avoidance. Had the TCM-06a or b maneuvers been necessary, that burn would have executed at EGA - 12 hours. The CARA timeline went as follows: at EGA - 28 hours was the OD DCO, with 4 hours to generate a new OD solution and at EGA - 24 hours send off the predicted trajectory and uncertainties to CARA. At EGA - 20 hours (TCM-06a/b - 8 hours) the CARA recommendation was reviewed, and if necessary the previously developed TCM-06a or b maneuvers had 8 hours for command sequence uplink.

As mentioned earlier in the introduction of this paper, the purpose of EGA-1 was to increase out the aphelion and put Lucy on a 2:1 orbital resonance trajectory with Earth. A significant ΔV boost is achieved from performing EGA-1, and while the exact ΔV gained depends on where the sphere of influence is calculated for the Earth, Figure 8(a) provides some visual context. Lucy was coming from the Sun-direction inside Earth's orbit, and had a low altitude targeted fly by of 352 km which bent the Lucy trajectory with respect to Earth 85° in the direction of the Earth heliocentric velocity.



(a) Earth-Centered fly by Diagram



(b) Vector fly by Diagram

Figure 8: Simplified EGA-1 fly by Geometry and Values

Figure 8(b) shows the full vector fly by diagram where $V_\oplus$ indicated by the green arrow is the Earth heliocentric velocity vector, while V_1 and V_2 in red are the pre- and post-fly by Lucy heliocentric velocity vectors respectively. The blue V_∞ vectors are the hyperbolic excess velocity vectors of Lucy with respect to Earth, again subscript 1 denoting pre-fly by, and subscript 2 is post-fly by. The turn angle δ is how much the

V_∞ vector was rotated about Earth, and the difference between V_1 and V_2 is the ΔV gained through the fly by. Of course Figure 8 is a simplification because the fly by does not happen instantaneously, so the vectors are in fact continuously changing slowly throughout the duration of the fly by.

After TCM-04a was executed the spacecraft trajectory was not corrected because the subsequent ODs demonstrated that the predicted trajectory was nearly on top of the EGA B-plane aim point, and the correction maneuvers would be small. Figure 9 is a zoom in from the previous B-plane plot shown in Figure 6. All the OD solutions leading up to EGA-1 were self consistent and stable, with the final reconstructed B-plane values of 14100.229 $\pm$ 0.0009 km in B·T and 5931.639 $\pm$ 0.001 km in B·R with an epoch of 16 October, 2022 11:05:39.923 $\pm$ 0.0001 sec. The final fly by altitude was 7 km higher than the targeted 352 km at 359.69 km.

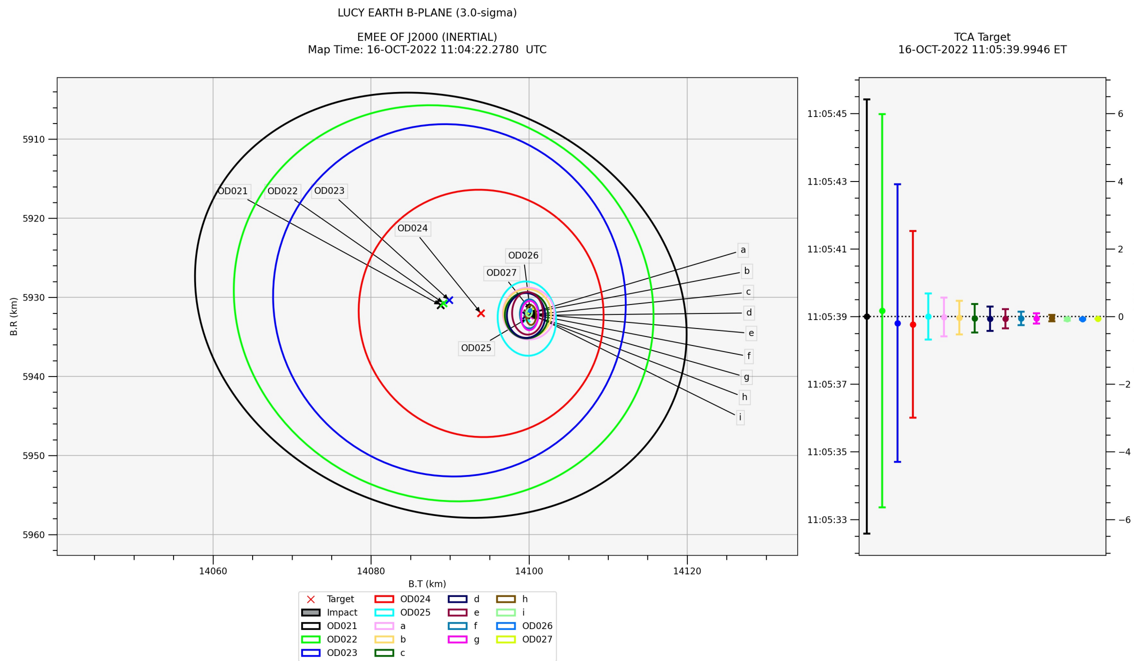


Figure 9: EGA-1 B-plane Progression OD021 - OD027

CONCLUSIONS

The navigation team successfully operated the Lucy spacecraft in its first year of flight from launch all the way through its first Earth fly by. Because of the excellent maneuver executions, and the stable predicted ODs, many of the planned statistical maneuvers were canceled. The OD team continues trending the spacecraft and refining the dynamical models to further improve the predicted trajectory which will be critical during the many upcoming asteroid encounters. The team is currently preparing for the Dinkinesh encounter on 1 November, 2023 which will also be the first use of optical navigation on this mission. The filter strategy for the encounters will be updated to include the estimation of the asteroid's set III parameters and GM. The uneven torque produced by the solar arrays is much less of an issue farther from the Sun, therefore fewer desats are likely to be required during later parts of the mission as well. This will have a positive impact on the estimated OD parameters with a low signal-to-noise ratio like the encounter asteroids' GMs.

ACKNOWLEDGMENTS

This work is supported by NASA under Contract 80GSFC18C0070. Lucy is the 13th mission in NASAs Discovery Program. Hal Levison of the Southwest Research Institute (SwRI), is the principal investigator.

Lockheed Martin Space Systems in Denver built the spacecraft and is providing flight operations. Goddard Space Flight Center and KinetX Aerospace are responsible for navigating the Lucy spacecraft.

REFERENCES

[1] Levison, H. F., "Lucy: Surveying the Diversity of the Trojan Asteroids: The Fossils of Planet," *47th Lunar and Planetary Science Conference*, 2016.

[2] Stanbridge, D., Williams, K., Williams, B., Jackman, C., Weaver, H., Berry, K., Sutter, B., and Englander, J., "Lucy: Navigating a Jupiter Trojan Tour," AAS 17-632, Stevenson, WA, 2017.

[3] "DSN Telecommunications Link Design Handbook," Tech. Rep. 810-005, Rev. E, Deep Space Network, Jet Propulsion Laboratory, California Institute of Technology, Jan. 2018.

[4] McElrath, T., Watkins, M., Portock, B., Graat, E., Baird, D., and Wawrzyniak, G., "Mars Exploration Rovers Orbit Determination Filter Strategy," *AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, American Institute of Aeronautics and Astronautics, Providence, Rhode Island, Aug. 2004.

[5] Antreasian, P. G., Bordi, J. J., Criddle, K. E., Ionasescu, R., Jacobson, R. A., Jones, J. B., MacKenzie, R. A., Meek, M. C., Pelletier, F. J., Roth, D. C., and Stauch, J., "Cassini Orbit Determination Performance During the First Eight Orbits of the Saturn Satellite Tour," .

[6] Geeraert, J. L., Leonard, J. M., Kenneally, P. W., Moreau, M. C., and Lauretta, D. S., "OSIRIS-REx Navigation Small Force Models," .

[7] Folkner, W. M., Williams, J. G., Boggs, D. H., Park, R. S., and Kuchynka, P., "The Planetary and Lunar Ephemerides DE430 and DE431," Tech. rep., Feb. 2014.

[8] Park, R. S., Folkner, W. M., Williams, J. G., and Boggs, D. H., "The JPL Planetary and Lunar Ephemerides DE440 and DE441," *The Astronomical Journal*, Vol. 161, No. 3, March 2021, pp. 105.