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Orbit Selection for the Proposed Lynx Observatory Mission

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LIST OF ACRONYMS AND DESIGNATORS

ACS	attitude control system
ATK	Alliant Techsystems, Inc. (now Northrop Grumman Innovation Systems)
CCD	charge-coupled device
CTO	Chandra-type orbit
DAO	drift-away orbit
DRO	distant retrograde orbit
DSN	Deep Space Network
GEO	geosynchronous Earth orbit
JWST	James Webb Space Telescope
IUS	Inertial Upper Stage
IXO	International X-ray Observatory
LDRO	Lunar Distant Retrograde Orbit
LEO	low Earth orbit
LSP	Launch Services program
LV	launch vehicle
MET	Mission Elapsed Time
NEN	Near Earth Network
PI	principal investigator
SAA	South Atlantic Anomaly
SE-L2	second Sun-Earth Lagrange point

LIST OF ACRONYMS AND DESIGNATORS (Continued)

TESS	Transiting Exoplanets Survey Satellite
TM	Technical Memorandum
TTI	Transfer Trajectory Injection
TTO	TESS-type orbit

TECHNICAL MEMORANDUM

ORBIT SELECTION FOR THE PROPOSED LYNX OBSERVATORY MISSION

1. INTRODUCTION

The Advanced Concepts Office design team performed several analyses and trades in support of orbit selection for the proposed Lynx mission, an x-ray observatory being submitted to the Astro2020 Decadal Survey. Though the descriptions in this Technical Memorandum (TM) focus on the Lynx mission, the approach and process for selecting the final orbit is applicable to a variety of proposed science and exploration missions.

To select the best orbit for the Lynx science, mission designers assembled a team of subsystem and discipline experts, in addition to mission analysts, to evaluate several candidate orbits. These discipline experts included members of the science and instrument team, power and avionics, thermal, propulsion, and environments. The goal was to clearly show the benefits and weaknesses of each orbit in the trade space and provide sound justification for the final selection. Discipline experts conducted trades and evaluated the results using a variety of methods including engineering judgement, rough estimates, and detailed calculations, and rolled the results into a final grade using a weighted grading method. The orbit options could then be ranked. The principal investigator (PI) for the mission, along with the science team, was given the task of final orbit selection.

The result of the trades indicated that a halo orbit about the second Sun-Earth Lagrange point (SE-L2), similar to the planned orbit for the James Webb Space Telescope (JWST), was the best choice for the Lynx mission. Details of how the team arrived at this selection are below.

2. LYNX MISSION SUMMARY

The Lynx X-ray Observatory is a flagship astrophysics mission being submitted to the Astro2020 Decadal Survey. The Lynx configuration appears somewhat similar to the Chandra X-ray Observatory but with larger optics, more sensitive instruments, and a larger propulsive capability. A more detailed description of the Lynx can be found in the report by Gaskin et al.,[1] and the interim report.[2] A list of the mission requirements that were assumed to have the most influence on the orbit selection process are listed in table 1.

Table 1. Driving requirements that impact orbit selection for the Lynx mission.

Property	Value
Mission duration	5 years (20-yr consumables)
Mission class	Risk class A
Serviceability	Design should include minimal provisions for servicing
Launch vehicle	Generic 2030s heavy lift (data provided by NASA Launch Services Program (LSP)
Deployment time	Maximum of 6 mo from launch to full capability
Science data	240 Gbits/day
Data latency	Not to exceed 48 hr
Observing efficiency	85%
Continuous observation time	10,000 s (can be interrupted for momentum unloading; not allowed to drive reaction wheel selection)

3. DETERMINING THE CRITERIA FOR EVALUATION

The criteria against which to evaluate each candidate orbit were selected based on the impact that the orbit may have on the various subsystems, maneuver budget, launch vehicle, and science efficiency. For example, the maximum distance from Earth that the observatory would achieve during the mission impacts the communications requirements (and consequently, power and pointing as well). Proximity of the observatory to Earth, the Moon, or other celestial objects, could impact thermal performance. Orbits with many perturbations (gravitational, aerodynamic, etc.) would affect pointing and propulsion. Orbits with complex outbound trajectories could affect propulsion requirements as well as other subsystems. Of course, the most important criteria was meeting the science requirements with the orbit. After discussing these topics, the team settled on several criteria against which to evaluate the candidate orbits, each listed and described in table 2. The rationale and weights are also shown.

As briefly stated above, the team selected a weighted grading method for evaluating the various orbit options. Each orbit option would be evaluated against these criteria by assigning a grade: A, B, or C. This simple three-category grading scheme allowed the team members to grade the various options quicker and with less discussion and debate than would a more complex and finely graduated scheme and was sufficient for the task of selecting the top two or three candidate orbits. An A indicated that the criteria being evaluated could be met in the orbit without concern. A grade of B indicated that the criteria being evaluated could be met with some risk or concern. Finally, a grade of C meant that the criteria could only be met by relaxing requirements to a point that would reduce the science return, limit launch options, etc., or require new technology development (for communications, for example). A grade of C did not disqualify an option—it only meant that the option posed significant challenges or increased risks. The evaluation team assumed that no orbit was included in the final trade space that could not possibly meet the requirements with some risk or technology development, so no grade below C was allowed. Additionally, since this exercise was to pick the best two or three orbits for presentation to the PI, orbits that would surely score low were not considered. For example, low lunar orbit was not a consideration since the high delta-v and maneuver costs, coupled with obscurations and thermal issues, would certainly remove it from contention. High delta-v insertion costs also eliminated geosynchronous Earth orbit (GEO). Elimination of orbits such as these, before they were even officially added to the trade space, was done based mostly on experience, intuition, and rough estimates. Those orbits are not discussed in this TM.

The overall grade for each candidate orbit was determined by two factors: (1) the score awarded for A, B, or C and (2) the weight given to each evaluation criteria as shown in the far-right column of table 2. The score awarded for the letter grades are shown in table 3.

Table 2. Evaluation criteria for orbit selection.

Criteria	**Description**	**Rationale**	**Weight (%)**
Science observing	Do objects obscure the field of view often? Do instruments need to go into standby often because of radiation hazards?	These things reduce science time, and limit the amount of the sky available for observation at a given time.	15
Launch vehicle	How large of a launch vehicle is required? Is the outbound trajectory complicated, requiring long coast phases and engine restarts for the launch vehicle?	Typically, larger launch vehicles are more expensive. Long coast phases may require special kits to limit boiloff, and can also reduce performance.	10
Delta-v	Total budget for the spacecraft, including outbound maneuvers, station-keeping, and disposal.	This not only affects the amount of propellant needed to be carried inside the limited spacecraft volume, but also the complexity of the mission.	15
Duration	Will the observatory remain close enough to allow for reasonable comm?	For some orbits, such as a drift-away option, the distance between the Earth and the observatory becomes very large after several years. This distance has a large impact on the design and power for the comm system.	10
Thermal	How stable is the thermal environment?	Large observatories with large optics require stable thermal environments for maximum performance. Shadowing and changing albedos of nearby objects present a thermal challenge.	15
Comm	How large must the comm system be to provide the science data downlink?	While a DAO poses the largest challenge (as the distance to Earth increases), other orbits pose problems as well. And the greater the distance, the more powerful the comm system needs to be (or longer contact times are required).	15
Environment	How severe is the radiation and meteoroid environment in this orbit?	Operation of the instruments can be affected by radiation. In addition, the observatory as a whole is susceptible to damage from meteoroids.	15
Serviceability	Does the orbit lend itself to serviceability?	Since the designs need to provide limited resources for serviceability, the ease of which a servicing spacecraft could reach the observatory should be considered. Alternatively, the observatory could maneuver to a servicing orbit.	5
		Total	100

Table 3. Possible grades used in the evaluation.

Grade	Score (%)
A	100
B	75
C	50

For each orbit, the individual criterion score is multiplied by the weight for that criterion. The total score for each orbit is the sum of these products. For example, if an orbit gets a grade of A for comm, then 15 points are added to the total score for that orbit. If comm gets a C, then only 7.5 points are added. An orbit that receives an A for all criteria gets a total score of 100.

With the criteria and scoring method agreed upon within the team, the next step was deciding which orbits to evaluate.

4. ORBITS INCLUDED IN THE TRADE SPACE

Orbit selection for the trade space was driven by experience and awareness of other flown and planned missions. Since many of the science team members were part of the Chandra observatory program, a Chandra-type orbit (CTO) was included. Several were also aware of the Transiting Exoplanets Survey Satellite (TESS) mission, an orbit that might offer some advantages. Other orbits included the JWST orbit (halo about SE-L2), a drift-away orbit (DAO) similar to the Kepler space telescope, and Lunar Distant Retrograde Orbit (LDRO). Each of these orbits is described in detail below. For each orbit, several parameters were determined (or estimated) by the mission analyst to allow the scientists and subsystem experts to evaluate the impact on their area. These parameters are listed, along with the impact of each on the design, in table 4.

Table 4. Mission analysis results used for trade space evaluation.

Parameter	Impact
Launch vehicle requirements (launch energy, coasts and restarts, etc.)	Impacts launch vehicle and cost
Mission delta-v (includes outbound maneuvers, station-keeping, and disposal)	Determines propellant load
Max and average distances from Earth and Moon	Impacts avionics and communications, as well as thermal; impacts obscurations and science observations
Outbound trajectory (both while on launch vehicle and free-flying)	Environments (multiple passes through radiation belts, etc.); required launch vehicle capability
Eclipse histories	Impacts power, thermal, and science

Note that these parameters, especially the delta-v budget, were roughly estimated for some of the options, since generating detailed values for all options was time prohibitive and would require a spacecraft design that had not yet started. Given the goal of selecting the best orbits for the Lynx mission, this approach was deemed acceptable. The reader may see differences in the parameters reported in this TM compared to the final results of the overall design study—those results are the ones used in the design of the subsystems. The results in this TM were used only to select the best orbits for the mission.

In generating the delta-v estimates, the following ground rules were used for values generated within the design team:

(1) A 5% attitude control system (ACS) tax was added to all maneuvers that used the main propulsion system.

(2) A 10% margin was added to nearly all deterministic maneuvers (exceptions are noted).

(3) A 25% margin (or better) was added to all statistical maneuvers (exceptions are noted).

For values retrieved from literature, the added margins were usually lower or zero, as these values often already included margin or were the results of statistical analyses. A rough order of magnitude delta-v budget was acceptable in the present work, as opposed to a more detailed analysis, because we were performing an overall comparison of options in the trade space, and a higher level of detail would not affect the results. The maneuver values could be further refined prior to the spacecraft design study. Also, while the values in the tables are reported to several digits, this does not reflect the accuracy of the numbers. The actual number of significant digits in the total delta-v estimates is about two, but since these numbers are considered intermediate values to be used as inputs into calculations by other discipline experts, they were not rounded.

The orbit parameters and maneuver budgets for each orbit option are listed in sections 4.1–4.6, followed by a section that compares the delta-v requirements, eclipse histories, and propellant estimates for each option. While momentum unloading estimates are not included in the delta-v budgets, consideration for that element is part of the grading process. For example, low Earth orbit (LEO) would surely require much more frequent momentum unloading than SE-L2 due to gravitational and aerodynamic torques, and this is reflected in the delta-v grading for those orbits. Please note that the orbit options are shown in tables throughout this TM and are not in any particular order.

4.1 Orbit Option: Chandra-Type Orbit

Given the experience of several science team members with the Chandra X-ray Observatory and its mission operations, a CTO was an obvious choice to be included in the trade space. The Chandra X-ray Observatory is named for the Nobel Prize winning astrophysicist Subramanyan Chandrasekhar and launched in 1999 aboard NASA's Space Transportation System (Space Shuttle Columbia). Chandra is one of NASA's Great Observatories[3] and can be characterized as an unqualified success. The orbit selected for the mission was the result of weighing many factors, not the least of which was the capability of the Space Shuttle. Since the shuttle could only deliver Chandra to LEO, achieving the final orbit was a function of Chandra's propulsion system and a kick stage called the Inertial Upper Stage (IUS). The IUS performed two firings before separating from the observatory. Chandra's onboard propulsion system then provided small maneuvers to achieve its final orbit. The nominal, highly elliptic 28.5° orbit was to be 140,000 km by 10,000 km altitude. This orbit was selected for several reasons: It was about the most that the IUS kick stage and the Chandra onboard propulsion system could achieve; it allowed the observatory to be above the radiation belts about 75% of the time during its 63.5-hr orbit; and it allowed uninterrupted observations that could last up to 2 days.

Due to gravitational perturbations over the life of the Chandra mission, the orbital inclination, apogee, and perigee have changed over time, as illustrated in figure 1, though the size of the orbit, hence the period, has remained essentially constant. The inclination of the orbit, originally

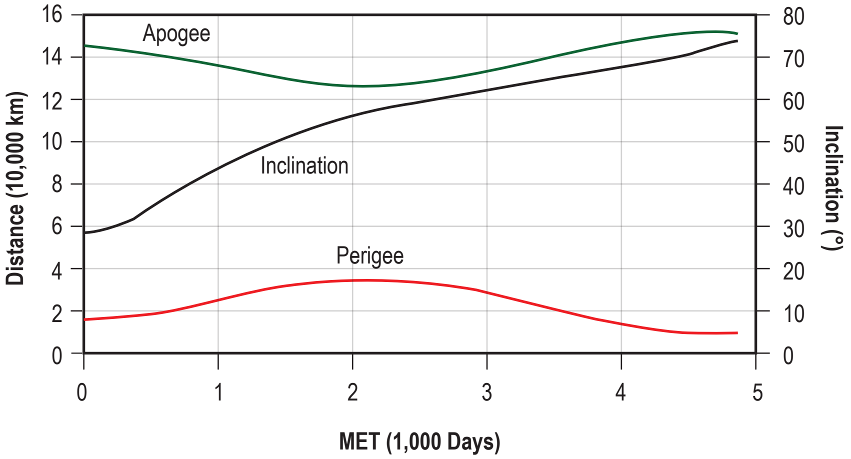


Figure 1. Chandra orbital parameters over time (beginning August 1999).

at 28.5°, has changed significantly. Coupled with other changing orbital parameters (such as the argument of perigee), it is possible over time for the observatory to pass through the GEO belt. While NASA standards for limiting orbital debris were not in place at the time Chandra was designed, they must be followed by future missions. Current NASA standards for limiting orbital debris, as specified in reference 4, require a disposal maneuver at the end of the mission so that spacecraft do not enter the GEO region post-mission. This required maneuver would have placed a heavy maneuver burden on Chandra and will require a large propellant load for Lynx. This maneuver is included in the delta-v budget generated for this trade space entry.

For the purposes of the Lynx study, the CTO was defined to be 16,000 by 133,000 km altitude with initial inclination of 28.5°, as shown in figure 2 as the red path.. The blue disk denotes the Earth's equatorial plane projected outward a few earth radii to GEO.

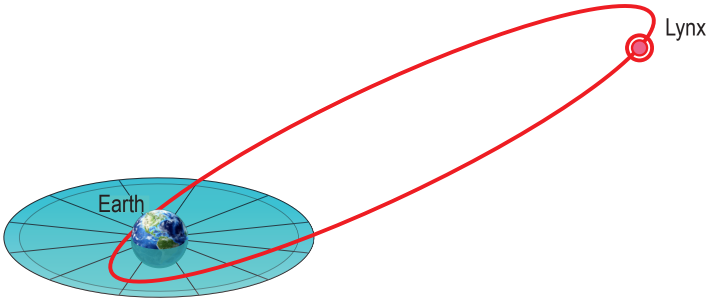


Figure 2. CTO assumption for Lynx.

In determining the delta-v budget for the mission, the team contacted NASA Launch Services program (LSP) for an estimated launch vehicle performance to the target orbit. Rather than have kick stages perform the maneuvers, the team assumed that determining whether the launch vehicle could place the observatory in the final orbit directly would be better (and easier). Indeed, the mission would require a Delta-IV Heavy or similar vehicle, as LSP estimated the performance of that vehicle to the target orbit to be not less than 6,000 kg, below the expected observatory mass. As a comparison, the same launch vehicle can provide slightly over 10,000 kg to an SE-L2 transfer, which illustrates the difficulty of achieving CTO.

In estimating the delta-v budget, only maneuvers occurring after launch vehicle separation were considered, since analysts assumed the observatory would start the mission in the target orbit. Neglecting the disposal maneuver, the delta-v budget would be small. However, guidance from the NASA Orbital Debris Program Office recommended the disposal orbit have a perigee such that it would not enter the GEO + 200 km region for 100 years. Given the uncertainty in the spacecraft model and the orbital parameters at the time of disposal, the team targeted a perigee of GEO + 1,200 km for the disposal orbit. This resulted in a delta-v of 302 m/s for the final disposal maneuver. While a large maneuver, this is much smaller that the maneuver required to force a controlled reentry into Earth's atmosphere.

The resulting delta-v budget for CTO is shown in table 5. As stated above, the total is dominated by the disposal maneuver at the end of the mission, a maneuver not required of Chandra. An estimate of the required propellant will be presented later in this TM.

Table 5. Delta-v budget estimate for CTO.

Event/Maneuver	Delta-v (m/s)	ACS Tax (%)	Margin (%)	Total (m/s)
Launch window	10	5	0	10.50
Post-TTI correction (dispersions)	20	5	0	21.00
Disposal	302	5	10	348.81
Maneuver total	332			380.31

4.2 Orbit Option: Transiting Exoplanets Survey Satellite-Type Orbit

NASA's Transiting Exoplanet Survey Satellite (TESS) mission will attempt to discover multitudes of exoplanets as they pass in front of (transit) their bright parent star. To achieve this mission, the TESS observatory needed long periods of unobstructed viewing. The chosen science orbit is a large orbit about Earth, a period half that of the Moon to balance perturbations, and very stable. It is also difficult to reach. Fortunately, a lunar gravity assist on the outbound trajectory allows a reasonable maneuver budget.

The TESS-type orbit (TTO) and transfer are shown in figure 3. The outbound trajectory, shown in red, includes three phasing loops prior to the lunar flyby, similar to the TESS mission. It is possible, however, for Lynx to be placed in a direct-transfer to the flyby, with no phasing loops.

After about a day of coasting, Lynx would perform a small correction maneuver and coast to the lunar flyby. The lunar gravity assist provides the energy to change the orbital inclination and raise the perigee. Further details of the orbital design can be found in reference 5.

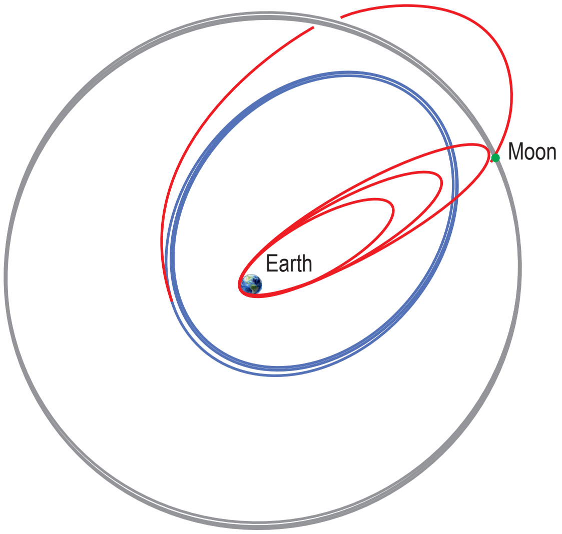


Figure 3. Illustration of a TTO (shown in blue).

The estimated total delta-v budget listed in table 6 takes values for many of the maneuvers from reference 5. Some maneuvers have no additional margin since the source already included margin, and others, such as the statistical maneuvers, come from statistical analyses and only need the same margin as deterministic maneuvers.

Table 6. Delta-v budget estimate for TTO.

Event/Maneuver	**Delta-v (m/s)**	**ACS Tax (%)**	**Margin (%)**	**Total (m/s)**
Launch window	10	5	0	10.50
Post-TTI correction (dispersions)	20	5	0	21.00
Deterministic maneuvers	150	5	10	173.25
Statistical maneuvers	40	5	10	46.20
Station-keeping (20 years)	0	5	10	0.00
Disposal	0	5	10	0.00
Maneuver total	220			250.95

No station-keeping is required for this orbit, as it is quite stable. At the end of the mission, the observatory could theoretically remain in that orbit indefinitely. The design team assumed that the orbit would meet the standards for limiting orbital debris, and no disposal is required. If the NASA standards were to change, a disposal from such a highly stable orbit would not be easy.

4.3 Orbit Option: Lunar Distant Retrograde Orbit

LDRO^6 appears as a kidney bean-shaped orbit when plotted in the Earth-Moon rotating frame, with the satellite orbiting the Moon in a retrograde motion. These orbits vary in size, but the period is around half a month. A plot of the LDRO assumed for the Lynx trade space is shown in figure 4.

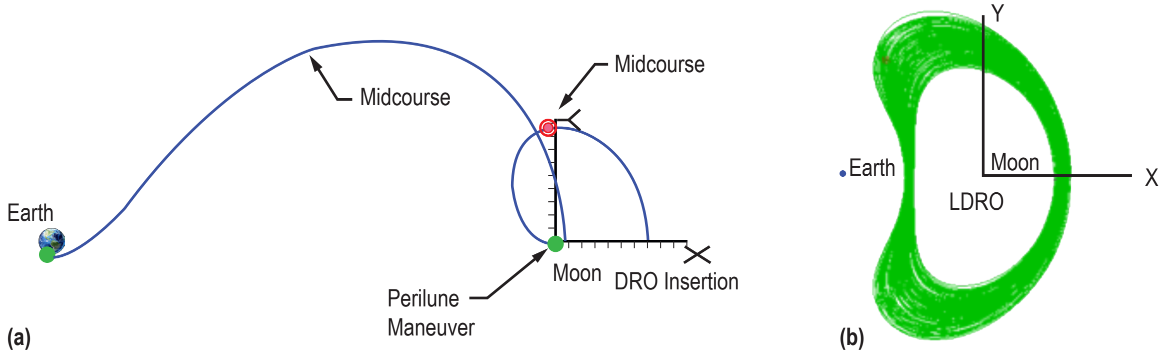


Figure 4. Plot of (a) the transfer trajectory to LDRO, and (b) the LRDO assumed for the Lynx trade space.

This orbit is not easy to reach from Earth, but a lunar gravity assist as shown in the diagram—coupled with a maneuver at perilune and followed by a midcourse maneuver—allows Lynx to reach the science orbit with a delta-v budget of less than 500 m/s, though this budget is still quite large. The detailed budget is presented in table 7. Although LDRO is a stable orbit, the team felt it necessary to include a disposal maneuver at the end of the mission to remove the observatory from the region where other missions (in particular human missions) may be placing assets in the future.

Table 7. Delta-v budget estimate for LDRO.

Event/Maneuver	Delta-v (m/s)	ACS Tax (%)	Margin (%)	Total (m/s)
Launch (C3 = –1.8 to –0.99 km^2/s^2)				
Launch window expansion	10	5	0	10.50
Post-TTI correction (dispersions)	20	5	0	21.00
MCC-1	50	5	10	57.75
Lunar flyby	162	5	10	187.11
MCC-2	155	5	10	179.03
LDRO insertion	3	5	10	3.47
Station-keeping (20 years)	5	5	10	5.78
Disposal	10	0	10	11.00
Maneuver total	415	–	–	475.63

4.4 Orbit Option: Drift-Away Orbit

As the name implies, DAO places the observatory on a trajectory with slightly positive energy relative to Earth, thus allowing Lynx to slowly (relatively speaking) drift away. The Kepler observatory employed a similar DAO,[7,8] an orbit chosen partly due to its lack of disturbing torques. Being away from gravitating bodies allowed Kepler to minimize momentum unloading and remove station-keeping requirements. These same benefits would allow a minimal delta-v budget for Lynx as well.

As the name implies, DAO sends the observatory on a trajectory that is slowly moving away from Earth. The spacecraft is actually placed into a slightly elliptical heliocentric orbit, which when plotted in the Sun-Earth rotating frame as shown in figure 5, causes loops. The overall effect of the orbital motion is for the observatory to slowly move away from Earth over time, until it reaches it maximum distance of about 2 AU on the opposite of the Sun from Earth, at which time the distance begins to decrease. Depending on the launch energy, the duration of this cycle can be decades. For the case of Lynx, the Earth-observatory distance reaches 1.8 AU in 20 years.

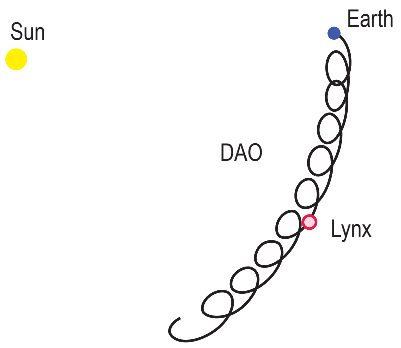


Figure 5. DAO, plotted in the Sun-Earth rotating frame. The loops are the result of the heliocentric orbit not being circular.

Given the lack of station-keeping requirements and midcourse corrections, the delta-v budget for this option is very small compared to others in the trade space. The maneuver budget is shown in table 8, with values based on a launch C3 of 0.61 km^2/s^2.

Table 8. Delta-v budget estimate for DAO.

Event/Maneuver	Delta-v (m/s)	ACS Tax (%)	Margin (%)	Total (m/s)
Launch (C3 = 0.61 km^2/s^2)				
Launch window	10	5	0	10.50
Post-TTI correction (dispersions)	20	5	0	21.00
Disposal	0	0	10	0.00
Maneuver total	30	–	–	31.50

4.5 Orbit Option: Sun-Earth Second Lagrange Point Halo

When plotted in the Sun-Earth rotating frame, this orbit appears to create a halo about the SE-L2, as shown in figure 6. Sitting at about 1.5 million km beyond Earth on the Sun-Earth line, the second Lagrange point (L2) moves along with Earth, so a satellite in a halo orbit will always remain in Earth's vicinity, provided station-keeping maneuvers are executed. Since these halo orbits are unstable, station-keeping is required, though the maneuver requirements are relatively small. Given the large distance between the spacecraft and Earth (and Moon), these orbits provide a stable thermal environment that is mostly free of gravitational disturbances, and provide excellent observation of the sky. If the observatory has a solar avoidance angle of 45°, for example, it can still see the entire sky in 1 year since the Lagrange point moves along with Earth, and after 6 months the solar exclusion zone would be in the opposite direction. The JWST[9] is one of many missions planning to use this orbit for observations.

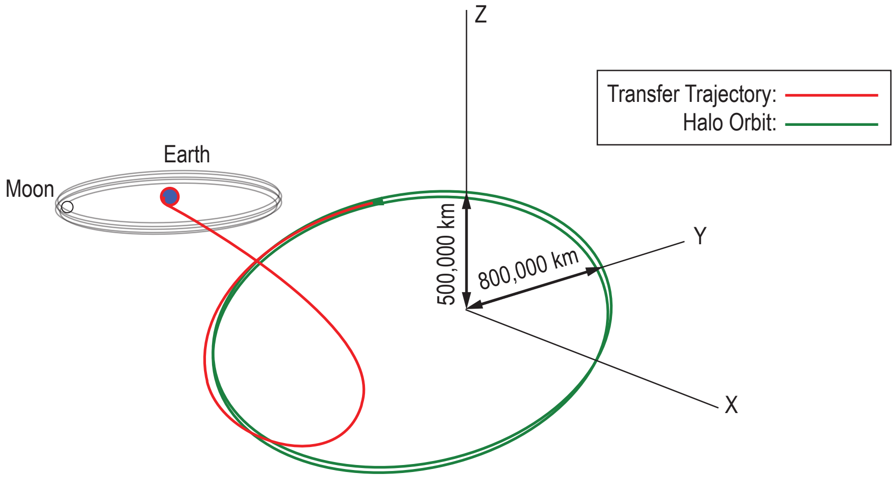


Figure 6. SE-L2 halo orbit (green) and transfer trajectory (red) selected for the trade space.

For Lynx, the team assumed the same halo size as has been investigated for JWST (see fig. 6). The main justification for this selection is to allow the use of JWST results for station-keeping, which includes additional delta-v as a result of momentum unloading. Similar to JWST, Lynx will be restricted in the thrust direction to avoid plume impingement on the sunshade and optics. This restriction causes a small residual delta-v during some momentum unloads, which affect the station-keeping budget. The Lynx team used the JWST numbers, as these have been analyzed through simulation,[9] and were a reasonable estimate for use in the Lynx trade space.

The delta-v budget was largely taken from JWST as well, with additional values for launch window expansion and midcourse corrections from the International X-ray Observatory (IXO)[10] design study. Though the fidelity of this maneuver budget is higher than for most other options in the trade space, the team did not feel that this provided the SE-L2 option with a biased advantage since budgets for the other options could be either high or low. The detailed budget used for evaluating the trade space is shown in table 9. Note that the first entry in the table, launch window, is a value added overall to increase the launch window duration and opportunity, and is taken from IXO. Also note that the station-keeping budget is taken from JWST, and includes addition margin. A small disposal maneuver is included to push the observatory outside the SE-L2 region once the mission is completed.

Table 9. Delta-v budget estimate for SE-L2.

Event/Maneuver	Delta-V (m/s)	ACS Tax (%)	Margin (%)	Total (m/s)
Launch ($C3 = –0.7\ km^2/s^2$)				
Launch window	10	5	0	10.50
Post-TTI correction (dispersions)	20	5	0	21.00
MCC-1	7.5	5	0	7.88
MCC-2	5	5	0	5.25
Other (contingency)	5	5	0	5.25
Station-keeping (20 years)	48.6	5	10	56.13
Disposal	1	5	0	1.05
Maneuver total	97.1	–	–	107.06

4.6 Orbit Option: Low Earth Orbit

LEO was included primarily as a reference for comparison, though due to the undefined configuration at the time of the trade space evaluation, the delta-v budget for this case has the highest uncertainty amongst all the various orbit options. This uncertainty is driven by the unknown aerodynamic torques on the observatory, since the configuration and pointing directions would greatly impact this estimate. The orbit is shown in figure 7.

Figure 7. LEO. For Lynx, the assumed orbit is 550 km circular, with 25.8° inclination.

The orbital parameters assumed for the operational orbit were 550-km circular altitude and 28.5° initial inclination, though only altitude needs to be maintained. The 550 km altitude was selected to minimize passage through the South Atlantic Anomaly (SAA) while staying above the major aerodynamic drag. Station-keeping estimates were generated using NASA's Debris Assessment Software (DAS), version 2.1, by assuming an area-to-mass ratio of 0.014 kg/m^3. Given the size of the observatory, a disposal maneuver consisting of a controlled reentry would be required from LEO, which is a substantial maneuver at the end of the mission. This maneuver, as well as the station-keeping estimate, is included in the delta-v budget shown in table 10. Note that this table does not include an estimate for momentum unloading. Given the gravitational and aerodynamic perturbations while in the orbit, this would surely be a substantial part of the propellant usage. If torque rods could be used for reaction wheel desaturation, this would certainly save propellant, but given the observing efficiency requirements, it was not known if this would be satisfactory at the time of the trade study.

Table 10. Delta-v budget estimate for LEO.

Event/Maneuver	Delta-V (m/s)	ACS Tax (%)	Margin (%)	Total (m/s)
Launch vehicle correction (dispersions)	20	5	0	21.00
Station-keeping (20 years)	160	5	10	184.80
Disposal	161	5	10	186.00
Maneuver total	341	–	–	391.80

5. COMPARISON OF THE ORBIT OPTIONS

Once the various orbits were defined, the next step was to compare the various options. In order for the discipline experts to evaluate and grade each orbit, they needed propellant mass, distances from Earth, and eclipse histories. Rather than include these datasets in the individual sections above, we present them in this section to make comparison more convenient.

Comparison of the estimated delta-v budgets provides some insight, but these values are much more meaningful if one can also compare the estimated propellant load. The delta-v budgets are shown in figure 8, with each budget being split into three major categories: (1) outbound, (2) maintenance, and (3) disposal. The outbound portion includes all midcourse corrections and deterministic maneuvers to reach the science orbit. Maintenance includes the station-keeping maneuvers for the entire mission. Disposal is the maneuver at the end-of-mission required to remove the spacecraft from certain regions of space, or to force a controlled reentry. Not all budgets include a disposal, and for some, the maneuver is too small to show in the plot.

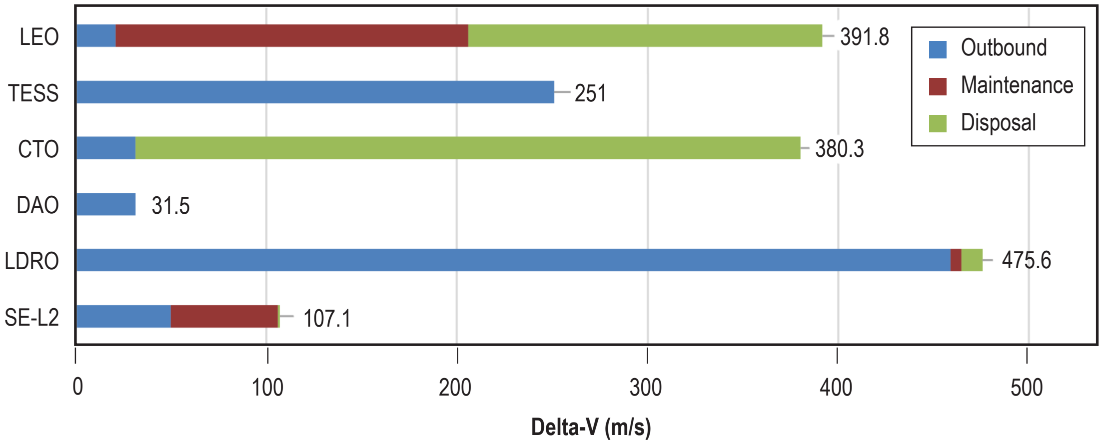


Figure 8. Comparison of the delta-v budgets (20 years consumables). To illustrate the sources of the totals, the budgets are split into outbound, maintenance, and disposal.

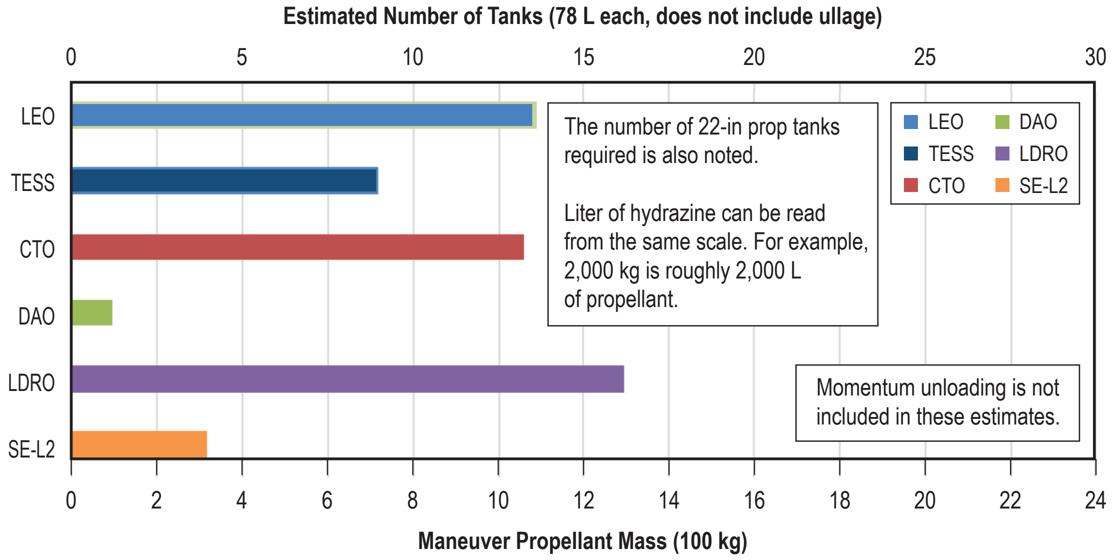
While the delta-v comparison gives an idea of the impact that the orbit option will have on the spacecraft, it is better to convert the maneuver budget into a propellant mass and an estimated number of propellant tanks, making it easier for nonmission analysts to participate in the trade space evaluation. Before going through the assumptions, it must be stressed that these estimates are only for comparison purposes and were not used by any discipline experts during the spacecraft design, only trade space evaluation. The tank volume requirements do not include any residuals, ullage, or additional pressurant tanks (if needed), nor was the specific impulse (I_{sp}) downgraded, as could be seen for a blowdown system.

Converting the delta-v values to a propellant mass and tank volume requires assumptions for I_{sp}, propellant type and density, initial observatory mass, and propellant tank size. These assumptions are listed in table 11.

Table 11. Assumptions for Estimating the Propellant Load.

Item	Value
Propellant system type	Monoprop blowdown
Propellant	Hydrazine
Density	1.021 g/cm^3
I_{sp}	218 s (constant)
Initial observatory mass	6,500 kg
Tank	ATK 22-in dia. spherical (78 L volume)

Given these assumptions, the team converted the maneuver budgets to propellant masses and tank requirements, as shown in figure 9. The bottom horizontal axis denotes the estimated propellant mass (which does not include momentum unloading). Since the density of hydrazine is 1.021 g/cm3, the same axis can be used to roughly estimate the volume in liters. For example, 1,000 kg of hydrazine is roughly 1,000 L. The top horizontal axis shows the estimated number of 22-in tanks required to hold the propellant load. From a previous design study conducted in 2015 for a similar mission named X-Ray Surveyor,[11] the precursor to the Lynx study, the team knew that eight propellant tanks was probably close to the practical limit. Given the volume limitations, finding space for more than eight tanks could be challenging.



The number of 22-in prop tanks required is also noted.

Liter of hydrazine can be read from the same scale. For example, 2,000 kg is roughly 2,000 L of propellant.

Momentum unloading is not included in these estimates.

Figure 9. Estimated propellant load, expressed as both a mass and as a number of 22-in tanks.

An examination of the results indicates that some orbits will likely be impractical. LDRO requires the highest propellant load, though after including momentum unloading in the LEO estimate, it would most likely exceed the LDRO prop load. CTO also requires a large amount of propellant, since it would require a disposal maneuver (not required of Chandra since it preceded disposal requirements). At the low end, DAO and SE-L2 appear to offer volume savings.

Another important criterion is the distance from Earth, which affects the communications system, including its type, size, and power. All but one of the orbit options are bounded to a region of space roughly within 0.01 AU of Earth. The one exception is DAO which, by definition, allows the spacecraft to slowly drift away from Earth over time. A comparison of the maximum distances from Earth for each orbit option is shown in figure 10. Figure 10 (a) shows the distances to scale except for DAO, which is shown to scale in figure 10 (b). In fact, the distance from Earth to the spacecraft on DAO can reach 2 AU (spacecraft opposite the Sun from Earth). Such great distances pose challenges to communications, as the large amounts of science data to download each day require high data rated to avoid lengthy or impractical contact times. This could require technology development for a laser communications system, for example.

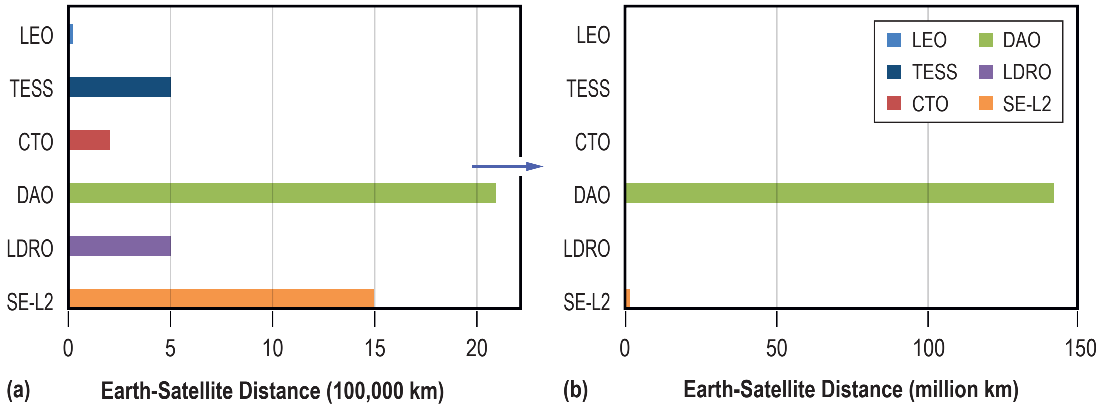


Figure 10. Maximum distance from Earth in 10 years: (a) Distances, to scale and (b) DAO distance to scale.

One other important criterion is the eclipse history. Eclipses affect the thermal design and performance of both the spacecraft and the optics. Stable thermal environments are better for the telescope optics, while frequent eclipses can cause thermal gradients across the optics, as well as gradients across the observatory structure, reducing performance.[12] Eclipses also affect the power system design. Long eclipses can require very large secondary batteries, and frequent eclipses—even if brief—impact the power system. Figure 11 provides the eclipse estimates for the orbits in the trade space. Figure 11(a) provides the average and worst-case eclipses for each orbit, as seen from simulations with Systems Tool Kit™ by Analytical Graphics, Inc. Looking only at the average and worst-case eclipse times, it would appear that SE-L2 is the best for eclipses, which makes sense as the halo orbit keeps the observatory outside the region where the Earth or Moon could come between the observatory and the Sun. LEO looks promising as well, when only looking at average eclipse times. On the other hand, LDRO appears to be the worst option for eclipses, with eclipse times averaging around 200 min and peaking at almost 12 hr, but this is misleading and is only one part of the evaluation criteria. The plot in figure 11(b) shows the percent of time the observatory would spend in eclipse during the mission. As mentioned previously, the SE-L2 halo is never eclipsed, which results in a very stable thermal environment. LEO, on the other hand, spends over 35% of mission time in eclipse, so while the average and worst-case eclipses are short, they occur every orbit, force the batteries to power the observatory, and result in an unstable thermal environment. While LDRO appeared to be a bad choice based on eclipse duration, the total time in eclipse is small, meaning that eclipses are rare. In fact, except for LEO, the percent of time in eclipse for each option is actually very small (less than 1%). Typical eclipse histories are plotted in figure 12 for the TTOs and CTOs, with eclipses due to Earth and the Moon noted separately. Note that the percentage for LEO is high, even though the eclipse durations are relatively short. Since there are many TESS- and Chandra-like orbits, these plots are only meant to show the general trend, but clearly show the different frequencies of eclipses for the orbits in the trade space.

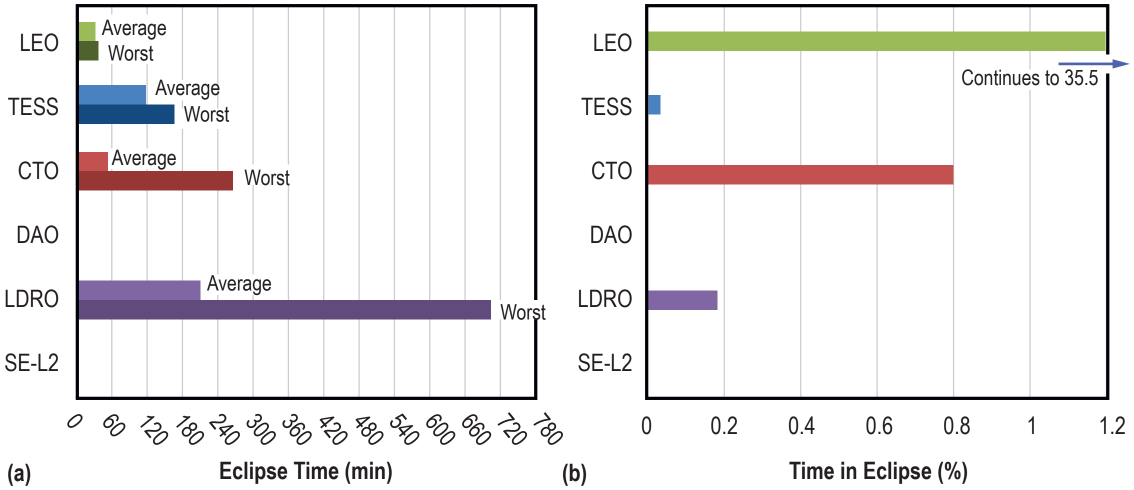


Figure 11. Eclipse estimates for each orbit considered: (a) Duration (average and worst case) and (b) percentage.

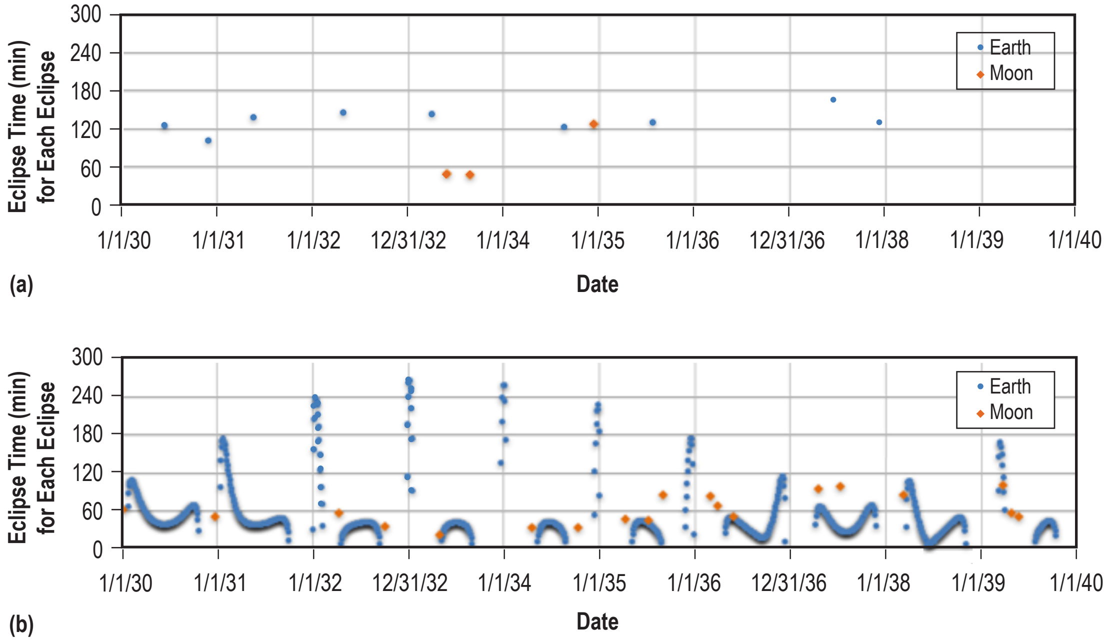


Figure 12. Example of eclipse histories over a 10-yr period for (a) the TTO and (b) the CTO.

6. EVALUATION OF THE ORBIT OPTIONS

With a complete set of data for orbit locations, propellant estimates, eclipse histories, and Earth-spacecraft distance, discipline experts could now evaluate and grade each orbit option. As described previously, each expert was tasked to use the data provided by the mission analysts and grade each orbit option based on the impact that the parameters would have on their design. Possible grades were A (best), B, and C (worst). In addition, each discipline expert was also asked to provide rationale for their grades. Table 12 lists the grades. The top row lists the final rank, based on the total score, for each orbit option. The total score for each option is shown in the third row, with 100 being the maximum possible. The grades shown in the table, which were used to calculate the total scores, were determined by the discipline experts. The weights used for each criterion (science observing, launch vehicle, etc.) were previously shown and explained in table 2. A grade of A is given 100%; B, 75%; and C, 50%; the overall score is determined by multiplying the grade by the weight for each criterion, and summing the resulting values. The grades are color-coded to make comparison easier. Justification for the grades is provided in tables 13–18, with each orbit option having its own table.

Table 12. Grades for the various orbit options in the trade space.

Rank	**1**	**4**	**3**	**5**	**2**	**6**
Orbit Option	SE-L2	DAO	LDRO	CTO	TESS	LEO
Total Score	91	81	84	73	86	68
Science observing	A	A	A	B	A	C
Launch vehicle	A	A	A	B	A	A
Delta-v	A	A	C	B	B	C
Duration	A	C	A	A	A	B
Thermal	A	A	B	C	B	C
Comm	B	C	A	A	A	C
Environment	B	B	B	C	B	A
Serviceability	B	C	B	C	C	A

Table 13. SE-L2: Grades and rationale.

Total Score	**91**	
Science observing	A	This orbit affords nearly unobscured observations.
Launch vehicle	A	SE-L2, DAO, and LDRO are roughly similar in LV requirements.
Delta-v	A	Budget is not bad, but the orbit maintenance adds up over 20+ years.
Duration	A	Stays roughly within 0.01 AU from Earth.
Thermal	A	Very stable.
Comm	B	Three times further than LDRO, making high data rates challenging, but can be accomplished using moderate power and high-gain pointing antennas.
Environment	B	Ionizing radiation: no geomagnetic shielding from solar particle events which drive total dose. Galactic cosmic rays drive single event effects. Meteoroids are same as interplanetary space.
Serviceability	B	Serviceability for this orbit is OK if one considers the spacecraft coming back to cis-lunar space for servicing, like ATLAST and LUVOIR. The delta-v requirements are minimal.

Table 14. DAO: Grades and rationale.

Total Score	**81**	
Science observing	A	This orbit affords nearly unobscured observations.
Launch vehicle	A	SE-L2, DAO, and LDRO are roughly similar in LV requirements.
Delta-v	A	No orbit maintenance nor correction maneuvers result in the lowest delta-v budget.
Duration	C	Reaches 0.3+ AU after a few years, 1 AU by 10 years.
Thermal	A	Very stable.
Comm	C	Would require a high-power system and would lose performance with distance.
Environment	B	Ionizing radiation: no geomagnetic shielding from solar particle events which drive total dose. Galactic cosmic rays drive single event effects. Meteoroids are same as interplanetary space.
Serviceability	C	Servicing is not possible for this orbit, as the distance continually increases.

Table 15. LDRO: Grades and rationale.

Total Score	**84**	
Science observing	A	Not as good as SE-L2 and DAO, obscurations from the Earth and Moon should nevertheless be very infrequent.
Launch vehicle	A	SE-L2, DAO, and LDRO are roughly similar in LV requirements.
Delta-V	C	Low orbit maintenance, but transfer trajectory does require some substantial maneuvers.
Duration	A	Always less than 600,000 km from Earth.
Thermal	B	Fairly stable, though there could be some shadowing during the mission.
Comm	A	LDRO and CTO would be similar systems being same order of distance (at CTO apogee). LDRO will provide nearly continuous NASA Deep Space Network (DSN) contact with minimal power required.
Environment	B	Ionizing radiation: no geomagnetic shielding from solar particle events which drive total dose. Galactic cosmic rays drive single event effects. Meteoroids are same as interplanetary space.
Serviceability	B	Since servicing items in this orbit is already being considered, this orbit is the best servicing option. However, getting to that orbit would not be easy for a launched spacecraft.

Table 16. CTO: Grades and rationale.

Total Score	**73**	
Science observing	B	Obscurations from the Earth and Moon are infrequent, but the passes through the radiation belts may force the instruments to be placed into standby mode frequently, impacting observation time.
Launch vehicle	B	CTO requires more performance (i.e., one or two more SRBs).
Delta-v	B	While Chandra has required little orbit maintenance, the new orbital debris standards may require a disposal maneuver at the end of any new missions planned for this orbit.
Duration	A	Always less than 200,000 km from Earth.
Thermal	C	Unstable. Thermal cycling, reflected and direct heat from Earth.
Comm	A	Available DSN link may be intermittent at times because of the highly elliptical orbit with close proximity to Earth, restricting specific link times, but this can be mitigated with longer DSN link times as needed.
Environment	C	Ionizing radiation environment is same as other candidates plus the passage through the radiation belts, which contributes significant total dose and single event effects. Moderate energy protons in outer magnetosphere can damage front-illuminated, charge-coupled devices (CCDs). Meteoroid environment is similar to others but with mild enhancement at perigee due to gravitational focusing (speeds up slower meteoroids), however spacecraft spends little time that low, and apogee is same interplanetary environment.
Serviceability	C	This orbit is difficult to get into, but launch vehicles can place a servicing spacecraft directly into the orbit. However, the servicing spacecraft may have to survive multiple passes through the radiation belts, making human servicing challenging.

Table 17. TTO: Grades and rationale.

Total Score	**86**	
Science observing	A	Similar to LDRO and not quite as good as SE-L2 and DAO, obscurations should nevertheless be very infrequent.
Launch vehicle	A	TESS gets an A for launch vehicle because, unlike CTO, the launch vehicle does not actually put the spacecraft into the final orbit. Rather, it places it on a highly elliptical trajectory to enable a lunar gravity assist.
Delta-v	B	The delta-v is not as high as for LDRO, but it is significant. Several maneuvers required for the outbound trajectory.
Duration	A	Always less than 500,000 km from Earth.
Thermal	B	Fairly stable, though there could be some shadowing during the mission.
Comm	A	Because of the higher inclination of the TESS orbit, there may be periodic differences in DSN atmospheric gain/losses, but overall, should not be a problem.
Environment	B	Ionizing radiation: no geomagnetic shielding from solar particle events which drive total dose. Moderate energy protons in outer magnetosphere can damage front-illuminated CCDs. Galactic cosmic rays drive single event effects. Phasing orbits accumulate slightly more dose especially to very thinly shielded materials. Meteoroids are same as interplanetary space.
Serviceability	C	Very challenging orbit to get into, so all missions would probably require the lunar gravity assist.

Table 18. LEO: Grades and rationale.

Total Score	**68**	
Science observing	C	Frequent eclipses, SAA, pausing observations for orbit maintenance maneuvers: all these plus more frequent momentum unloading would really cut into science time.
Launch vehicle	A	Greatest launch vehicle performance is to LEO.
Delta-v	C	Controlled reentry required. Orbit maintenance required to avoid reentry during lifetime, which can get expensive for long missions.
Duration	B	Duration is completely dependent on station-keeping and orbit maintenance.
Thermal	C	Unstable. Thermal cycling, reflected and direct heat from Earth.
Comm	C	In LEO, the NEN will be used for comm. S-band is limited to 5 Mbps per customer, and X-band is limited to 10 Mbps, which is not sufficient for the mission data rate required.
Environment	A	In LEO, the observatory is shielded from solar particle events unless at high geomagnetic latitudes. Single event upset rates for proton-sensitive parts can increase during SAA passes. Orbital debris is a significant hypervelocity impact risk. Meteoroid environment is similar to others but with mild enhancement due to gravitational focusing (speeds up slower meteoroids).
Serviceability	A	Best servicing option.

With an overall score of 91 out of a possible 100, the SE-L2 halo orbit appears to be the best choice and is the only option that does not have any grades of C. The TTO and LDRO are not far behind, though each poses a challenge in one area: serviceability for TESS, and delta-v for LDRO.

Looking at the overall scores, it is obvious that LEO would be a challenging orbit if selected for the Lynx mission. Poor scores in many areas effectively eliminate it from contention. The CTO also receives a low score, primarily due to the environment and serviceability, as well as for thermal considerations (though the thermal grade is likely a high C.) The DAO score seems like an acceptable option at 81, but the distance over time would impact avionics quite substantially, possibly requiring a technology development for laser communications from such great distances.

7. CONCLUSION: SELECTION OF THE BASELINE ORBIT FOR LYNX

The three highest-ranking orbits—SE-L2, TESS, and LDRO—were recommended to the science team, along with supporting documentation and discussion. After reviewing the materials, and with considerations for currently planned large astronomical missions, the Lynx science team selected the halo orbit about SE-L2 as the baseline orbit for the proposed mission. The orbit to be used in the spacecraft design study would be similar to that which is planned for JWST (see fig. 6).

The most beneficial aspects of the SE-L2 orbit appear to be the stable thermal environment, relatively unobscured observations that allow full sky coverage in 1 year, a relatively high launch vehicle capability to the transfer orbit (10,000 kg per the NASA LSP guidance for future heavy vehicles in the 2030s), and a moderate delta-v budget. Additionally, servicing in this orbit may be possible either by sending a servicing craft directly to the orbit or perhaps maneuvering back to an Earth-Moon libration point orbit[13] with minimal delta-v requirements, though these servicing technologies are yet to be developed.

With the baseline orbit selected, the design team could pursue the spacecraft design and refine the maneuver budget and momentum unloading requirements for the mission. The results of this exercise can be found in the Lynx Interim Report.[2]

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14. ABSTRACT

The Advanced Concepts Office design team performed several analyses and trades in support of orbit selection for the Lynx mission, an x-ray observatory proposed as a follow-on to Chandra. Mission designers assembled a team of subsystem and discipline experts, in addition to mission analysts, to evaluate several candidate orbits. The team conducted trades, evaluated the results using a variety of methods, and then rolled the results into a final grade using a weighted grading method. The result of the trades indicated that a halo orbit about the second Sun-Earth Lagrange point (SE-L2) was the best choice for the Lynx mission.

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