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PHASE CONTROL AND ECLIPSE AVOIDANCE IN NEAR RECTILINEAR HALO ORBITS

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The baseline trajectory proposed for the Gateway is a southern Earth-Moon L_2 Near Rectilinear Halo Orbit (NRHO). Designed to avoid eclipses, the NRHO exhibits a resonance with the lunar synodic period. The current investigation details the eclipse behavior in the baseline NRHO. Then, phase control is added to the orbit maintenance algorithm to regulate perilune passage time and maintain the eclipse-free characteristics of the Gateway reference orbit. A targeting strategy is designed to periodically target back to the long-horizon virtual reference if the orbit diverges over time in the presence of additional perturbations.

INTRODUCTION

The Gateway[1] is proposed as an outpost in deep space: a proving ground for deep space technologies and a staging location for missions to the lunar surface and beyond Earth orbit. Envisioned as a crew-tended spacecraft, the Gateway will be constructed over time as various components are delivered either as co-manifested payloads with Orion or independently without crew presence. For power and thermal reasons, the Gateway spacecraft must avoid spending long spans of time in the shadow of either the Earth or the Moon. Eclipses by the Moon's shadow tend to be short, less than 90 minutes. The Earth's shadow, however, can lead to eclipses lasting several hours. It is important to avoid long passages into the shadow of the Earth.

The current baseline orbit for the Gateway is a Near Rectilinear Halo Orbit (NRHO) near the Moon.[2] The selected NRHO is part of the L_2 halo orbit family, oriented with apolune in the southern hemisphere. The specific orbit within the family exhibits a 9:2 resonance with the lunar synodic period, so that the Gateway completes 9 revolutions within the NRHO every two lunar synodic months. With a perilune radius ranging from about 3,200 km to about 3,550 km and an apolune radius varying between 70,000 km and 72,000 km, Gateway's baseline orbit is designed to avoid eclipses by the Earth's shadow.[3] The baseline NRHO appears in Figure 1 in Earth-Moon and Sun-Earth rotating views.

A spacecraft in an NRHO experiences perturbations and errors; examples include solar pressure modeling errors, maneuver execution errors, navigation errors, residual Δv from slews and momentum desaturations, docking and plume impingement perturbations, and venting from crew vehicles. The baseline NRHO is nearly stable, but in the presence of errors and perturbations, regular orbit maintenance maneuvers are required to maintain a spacecraft in the orbit for extended durations. Low-cost stationkeeping is achieved through an *x*-axis crossing control method[4,5,6] that employs a virtual reference trajectory. Previous analyses control the orbit itself, maintaining the spacecraft in an NRHO. However, they do not control the phase within

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the orbit, and over time the spacecraft drifts from the baseline. With sufficient drift, the spacecraft is at risk of long eclipses by the Earth's shadow. The current investigation explores phase control within the NRHO to maintain the eclipse-free characteristics of the virtual reference. The x-axis crossing control method is augmented to maintain periapse passage time, thus maintaining the eclipse-free phase achieved in the baseline NRHO. Then, a rendezvous strategy is developed to target back to the long-horizon NRHO in cases where the orbit evolves over time away from the virtual reference in the presence of large perturbations.

15-YEAR BASELINE NRHO: OSCULATING PARAMETERS AND ECLIPSES

Historically, halo orbit missions including WIND[7] and ARTEMIS[8] have operated without a reference trajectory. Halo orbit stationkeeping is effective and inexpensive without targeting parameters from a pre-defined reference. However, as the L_2 halo family approaches the Moon, the costs and computation time associated with orbit maintenance are decreased by employing a baseline trajectory as a virtual reference, that is, as a catalog of targeting parameters.[9] Adhering strictly to a reference orbit is unnecessarily expensive. Instead, by targeting specific parameters extracted from a virtual reference trajectory, a spacecraft can maintain the orbit for low propellant costs while retaining characteristics of the reference. For the Gateway, remaining near the reference is important for avoiding long eclipses from the Earth's shadow as well as for facilitating mission design for spacecraft visiting the Gateway, including Orion, lunar lander elements, logistics modules, and others.

The current 15-year baseline orbit for the Gateway spacecraft is designed by Lee[3] in an ephemeris model that includes N-body gravitational forces from the Sun, Earth, Moon, and the Jupiter system barycenter. The Moon is modeled with an 8x8 gravity field, while the other three bodies are considered point masses. Non-gravitational forces, including solar radiation pressure (SRP), are not included in the force modeling. The orbit extends from January 2020 to February 2035, and other than small discontinuities in velocity to maintain the almost-stable orbit (averaging less than 1.9 mm/s per revolution), the NRHO is a ballistic trajectory. The full 15-year ephemeris is plotted in Figure 1a in an Earth-Moon rotating view and in Figure 1b in a Sun-Earth rotating view.

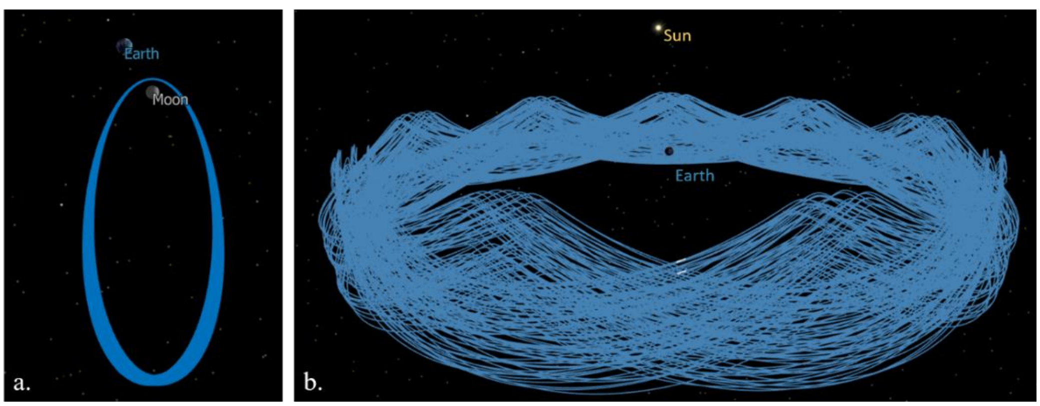

Figure 1. 15-year reference NRHO in Earth-Moon (a) and Sun-Earth (b) rotating views

Over the 15-year span, the mean orbital period (time from one perilune passage to the next) of the Gateway NRHO ranges from 6.26 days to 6.76 days, with a mean value of 6.56 days. Similarly, the mean perilune radius is 3,366 km with a minimum value of 3,195 km and a maximum value of 3,557 km. The apolune radius can be as large as 71,849 km, or as small as 70,005 km, with an average value of 71,100 km. Osculating parameters are summarized in Table 1. Further details on the generation and characteristics of the baseline NRHO appear in a white paper.[3]

Table 1. Osculating Gateway orbital parameters over 15 years

	Orbital period (days)	Perilune radius (km)	Perilune altitude (km)	Apolune radius (km)	Apolune altitude (km)
Minimum	6.26	3,195	1,458	70,005	68,267
Mean	6.56	3,366	1,629	71,100	69,363
Maximum	6.76	3,557	1,820	71,849	70,112

Spacecraft in cislunar orbits can experience eclipses from the shadows of both the Earth and the Moon. In an NRHO, lunar eclipses tend to be short, but passages through the Earth's shadow can be hours in duration.[3] For power and thermal reasons, eclipses longer than 90 minutes are undesirable. The Gateway baseline trajectory exploits the resonance with the lunar synodic period to avoid long eclipses by setting up a repeating geometry. This repetition is apparent when the trajectory is viewed in the Sun-Earth rotating frame, as in Figure 1b. Crossings of the ecliptic plane represent occasions when the spacecraft is at risk of passing into the Earth's shadow; ecliptic plane crossings and perilune passages are plotted in the Earth-centered Sun-Earth rotating frame in Figure 2a. The direction of the Earth's shadow is marked; note that neither perilune passages nor ecliptic plane crossings coincide with the positive Sun-Earth X axis. The baseline NRHO is, thus, deliberately oriented such that ecliptic plane crossings do not occur when the Earth lies between the spacecraft and the Sun.

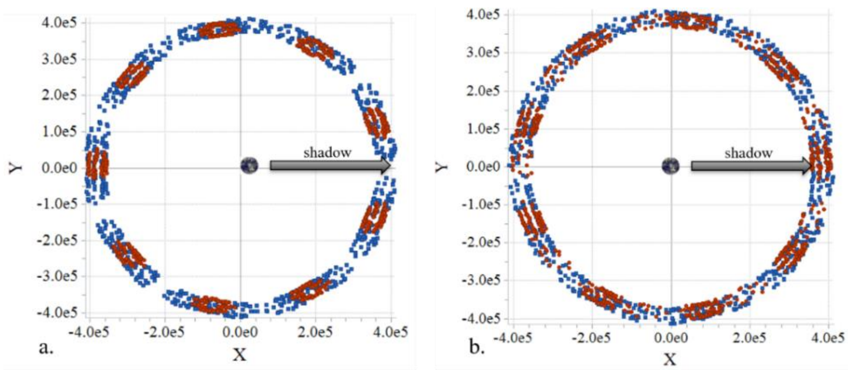

Figure 2: Ecliptic plane crossings (blue) and perilune passages (red) in the Sun-Earth rotating frame. 15-year Baseline NRHO (a) and one individual 15-year Monte Carlo trial (b)

The 15-year baseline NRHO only experiences two partial eclipses from the Earth's shadow, occurring during its fourteenth and fifteenth years. The eclipses in the reference NRHO from the Earth's shadow are marked in white in Figure 1b and detailed in Figure 3a. Although both penumbral shadows last longer than 90 minutes (denoted with a horizontal black line in Figure 3a), the spacecraft never passes into complete eclipse. The 2033 eclipse reaches 16%, while the shadow in 2024 has a maximum coverage of 22%. It is expected that both eclipses could be easily avoided by small adjustments to the trajectory.

Eclipses by the Moon are avoided in the first 6 months of the baseline orbit but occur relatively frequently thereafter. The pattern of lunar shadow durations over time appears in Figure 4. The maximum time in penumbral shadow is 76 minutes, and the maximum total eclipse duration is 73 minutes. An annual period is apparent in the pattern of lunar shadow durations over the 15-year propagation.

DYNAMICAL MODEL AND ERROR ASSUMPTIONS

In the current analysis, N-body differential equations and planetary ephemerides are employed. The relative position of each perturbing body with respect to the central body is instantaneously computed by employing NAIF SPICE ephemeris data. The Moon is selected as the central body for numerical integration in the J2000 inertial frame. The Earth and Sun are included as point masses, and the Moon's gravity is modeled using the GRAIL (GRGM660PRIM) model truncated to degree and order 8. Solar radiation pressure (SRP) acting on a sphere is also included in the force modeling of the simulated spacecraft, but not in the generation of the baseline NRHO.

For simplicity, the Gateway is considered to be uncrewed. A baseline set of errors is defined. Each orbit maintenance (OM) maneuver is associated with a navigation error on the spacecraft state; 3σ position errors of 1 km and velocity errors of 1 cm/s are assumed. Maneuver execution errors are applied in a random direction to each OM burn with 3σ values of 1.5% in magnitude and 1° in direction with an additional fixed component of 1.42 mm/s (3σ). Mismodeling in SRP assumptions are assumed at 15% error in area and 30% error in coefficient of reflectivity (3σ); the spacecraft is assumed to have an area to mass ratio of 0.01 m^2/kg. Momentum wheel desaturations are assumed to occur 4 times per revolution: once near apolune prior to OM burns, and the rest centered near perilune as the spacecraft experiences gravity gradient torques. A translational Δv component with a 3σ value of 1 cm/s is applied in a random direction. Perturbations are implemented as Gaussian errors with zero mean, unless otherwise specified. The baseline errors are summarized in Table 2, along with large and small bounding cases.

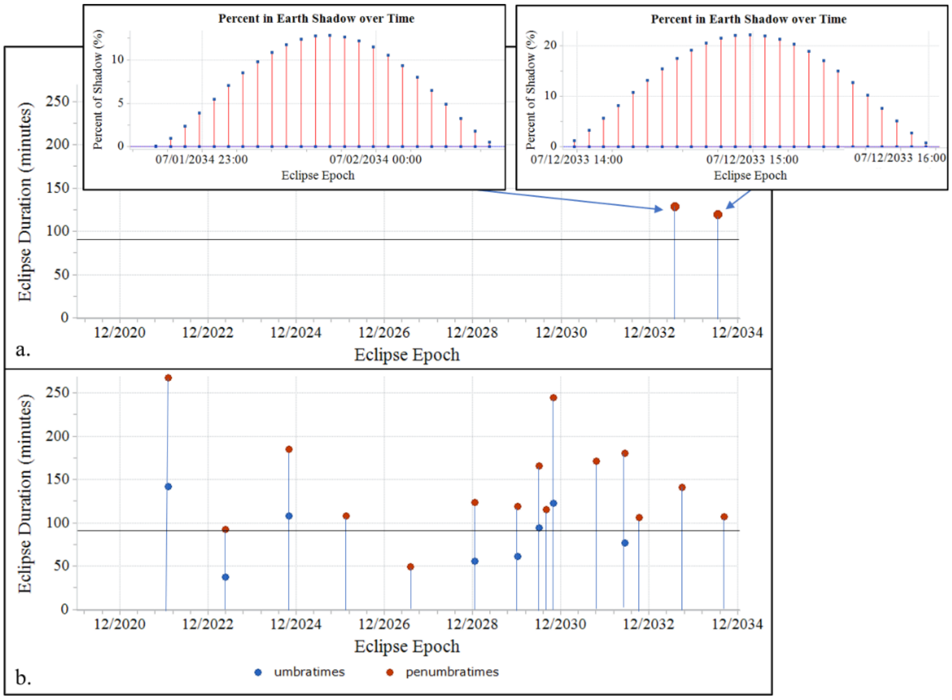

Figure 3: Eclipses from the Earth's shadow in the 15-year baseline NRHO (a) and in an individual Monte Carlo trial (b)

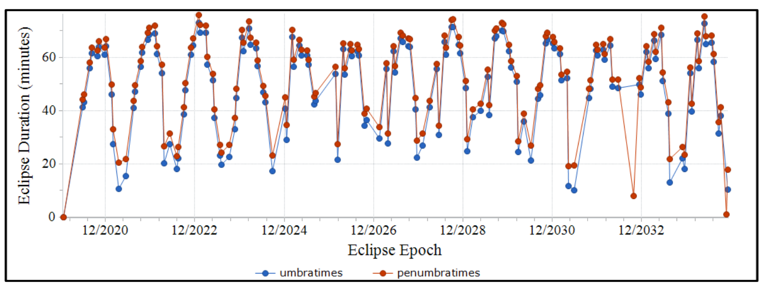

Figure 4: Eclipses from the Moon's shadow in the 15-year baseline NRHO

Changing error assumptions can significantly affect the orbit maintenance costs. Adding multiple desaturations near perilune, which is expected for larger Gateway configurations, leads to increased costs. Similarly, larger translational Δv values resulting from desaturation burns executed by misaligned or unbalanced thrusters significantly affect stationkeeping propellant use. Perturbations associated with crewed visits, including docking forces, unbalanced venting from Orion, and additional desaturations, all increase the cost of orbit maintenance. A small sensitivity study is performed to assess the effects of changing the assumptions in Table 2. A concurrent study explores orbit maintenance and attitude control costs for various crewed and uncrewed Gateway configurations.[10]

Table 2. Uncrewed Error Models: Baseline assumptions

		3σ Value			Notes		
	Error Type	small	baseline	large	small	baseline	large
SRP errors	Srp area Error % Srp CR Error %	30 15	30 15	30 15	a/m = 0.001 m^2/kg	a/m = 0.01 m^2/kg	a/m = 0.05 m^2/kg
Desat errors	Random Δv (cm/s)	0.01	1	3	0 at perilune, 1 prior to OM Δv	3 at perilune, 1 prior to OM Δv	5 at perilune, 1 prior to OM Δv
Navigation errors	Position (km) Velocity (cm/s)	0.1 0.1	1 1	10 10	at each OM Δv	at each OM Δv	at each OM Δv
Maneuver execution errors	magnitude % fixed (mm/s) direction (deg)	0.75 0.71 0.5	1.5 1.42 1	3 2.84 2	at each OM Δv	at each OM Δv	at each OM Δv

NRHO ORBIT MAINTENANCE

Without orbit maintenance, a spacecraft in an NRHO departs the vicinity of the orbit within about 5-20 revolutions, depending on the perturbations acting on the object. An x-axis crossing control algorithm[4,5,6] is identified as a low-cost, robust method to maintain the spacecraft in the NRHO for long-term missions. In its simplest form, the algorithm targets a single component of the baseline NRHO. A maneuver is designed at each apolune to target the x-component of rotating velocity, v_x, 6.5 revolutions downstream at the x-axis crossing near perilune (or at perilune itself) along a receding horizon. The algorithm maintains the spacecraft in the NRHO for multiple years at low propellant cost. However, since only a single component of the virtual reference is targeted, the spacecraft drifts from the baseline NRHO over time. This drift can lead to long eclipses from the Earth's shadow. To avoid such eclipses, the x-axis crossing control algorithm is augmented to maintain the phase of the spacecraft within the NRHO, and, thus, to retain the eclipse-free characteristics of the baseline NRHO.

Short-horizon orbit maintenance maneuvers: targeting v_x only

The simple x-axis crossing control orbit maintenance algorithm is summarized as follows. At (or near) each apolune passage, a differential corrector is employed to design a maneuver that delivers a velocity

$$v_x = v_{xref} \pm v_{xtol} \tag{1}$$

where v_x is the x-component of rotating velocity at the controlled spacecraft's perilune passage, v_{xref} is the x-component of rotating velocity along the baseline NRHO at its respective perilune passage, and the tolerance v_{xtol} is set to 0.45 m/s. The targeting horizon is initially set to 6.5 revolutions, so that $v_x = v_{xref}$ is achieved 6.5 revolutions downstream from the maneuver. If the targeter fails to converge, the horizon is reduced successively until convergence is achieved. (Note that for the 9:2 NRHO, the current algorithm is generally successful for horizons of 0.5 revolutions, 2.5 revolutions, 3.5 revolutions, etc., but *not* for a targeting horizon of 1.5 revolutions.[5] This correlation between targeting horizon and algorithm success is related to the stability properties of the NRHO. Different orbits experience different behavior with respect to horizon length, and algorithm adjustment can generally result in success for any horizon length.[11]) A longer horizon generally equates to lower cost, but longer targeting horizons increase computation time and decrease convergence rates. A horizon of 6.5 revolutions is empirically selected as a compromise between computation speed, robust convergence, and total orbit maintenance Δv. This simple algorithm mirrors the algorithm applied to both the ARTEMIS and WIND halo orbiters. It effectively maintains the Gateway spacecraft in orbit for multiple years[4,5,6] for low cost in both crewed and uncrewed Gateway scenarios. However, the spacecraft drifts from the baseline NRHO, leading to long eclipses and complicating planning for visiting vehicles. The drift from the reference orbit is apparent in Figure 5. The perilune passage time drift as compared to the baseline NRHO appears in Figure 5a for 100 Monte Carlo trials of an uncrewed Gateway, each propagated for three years in the presence of error models as summarized in Table 2. At the end of the three-year propagation, the drift in perilune passage time can reach more than 30 hours. Similarly, the drift in position components measured at perilune can surpass 100 km, as in Figure 5b. While this drift is not itself necessarily concerning, an increasing secular trend is visible, which continues in longer propagations. Each orbit maintenance burn remains between 3 cm/s (the minimum allowed burn magnitude) and about 20 cm/s. The mean annual cost for this 100-trial simulation is 0.9 m/s.

The simulations in Figure 5 on the left assume that the targeting maneuvers are placed at apolune. The resulting burn directions are approximately uniform, where the direction is generally aligned with the stable mode associated with the halo orbit.[6,8,9] The rotating x, y, and z components of the OM burn unit vectors over a year for 100 Monte Carlo trials are plotted as a function of time in the Earth-Moon rotating frame in Figure 6a. The burn vector is relatively consistent; variations follow a distinct pattern with a period of a lunar month. The burn directions and locations are plotted in 3D in the Earth-Moon rotating frame in Figure 6b. The OM burns have a small z component, existing mostly in the x-y plane. Each unit vector is plotted in Figure 6c. Figure 6a-c demonstrate the consistency of the burn direction when v_x is targeted from a consistent location along the NRHO. Note that the direction can be generally towards or away from the Earth along the stable mode. The sign is a function of the statistical errors acting on the spacecraft from one revolution to the next; since the burns are not deterministic, they cannot be planned multiple revolutions in advance. Note that the low-cost, consistently-directed maneuvers are achieved by employing a simple differential corrections targeter; optimization is not required.

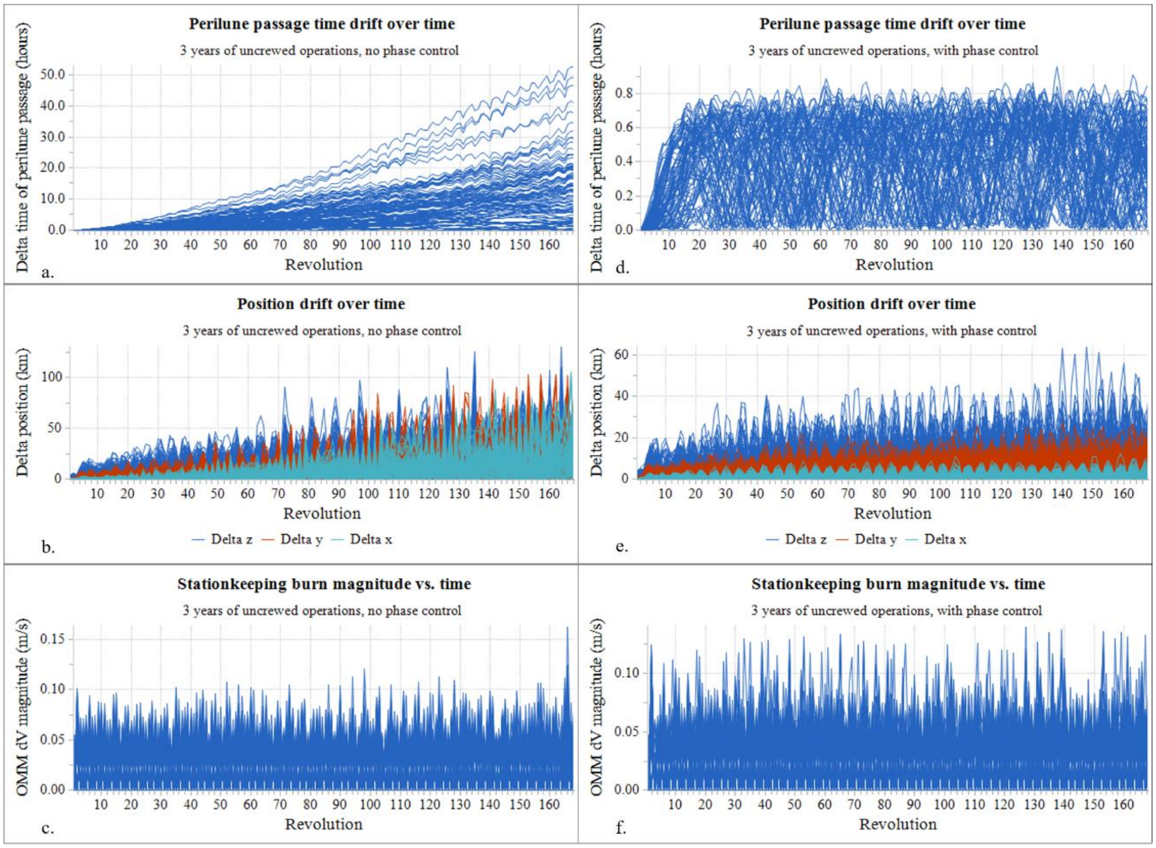

Figure 5. Drift in perilune passage time (top) and position components at perilune (middle), and stationkeeping burn magnitudes (bottom), without phase control (left) and with phase control (right).

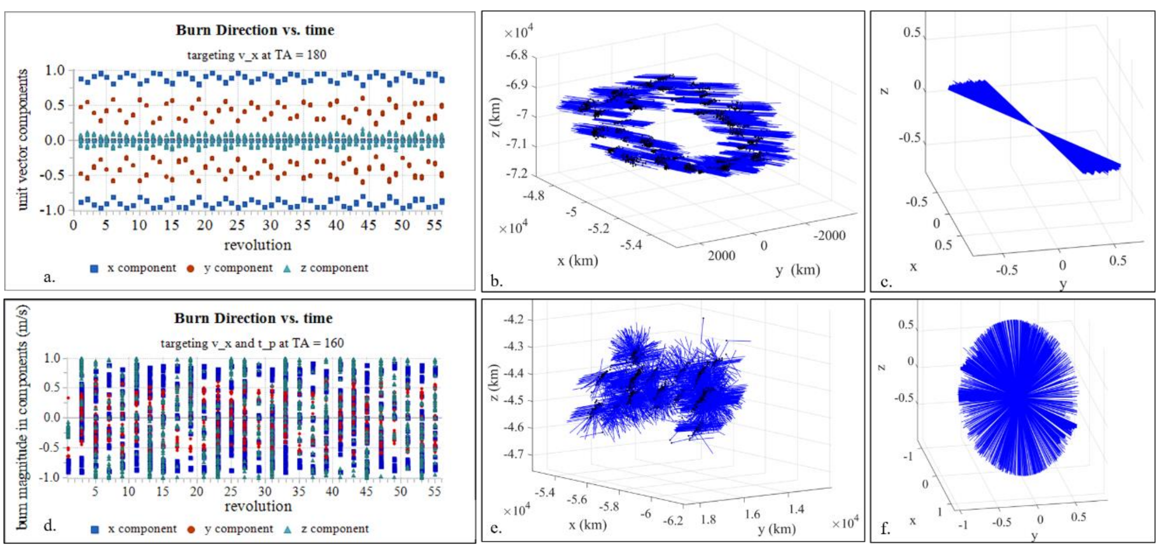

Figure 6. Burn unit vector components as a function of time (left), burn location and direction plotted in Earth-Moon rotating coordinates (middle), and the burn unit vector (right) for OM burns targeting v_x at TA = 180° (top) and targeting v_x and t_p at TA = 160° (bottom).

Over longer simulations encompassing the 15-year Gateway lifetime, the drifts in position and timing from the reference orbit apparent in Figure 5a-b continue to increase. Results from a 15-year Monte Carlo simulation of 100 trials appear in Figure 7 with baseline assumptions as defined in Table 2. While each of the trials successfully converges for the full 15-year simulation, the perilune passage time can drift by over 600 hours, as is apparent in Figure 7a. The spacecraft, thus, risks drifting into long eclipses from the Earth's shadow. The ecliptic plane crossings and perilune passages from one sample 15-year propagation appear in Figure 2b; note that the positive X axis is no longer clear of crossings. The resulting eclipses from this sample propagation appear in Figure 3b. The longest eclipse spans more than 4 hours. In addition, the large variations in the orbit lead to corresponding large variations in total OM cost. The cumulative Δv over the 15-year simulation appears in Figure 7b. The costs range from a minimum of 13 m/s to a maximum of 49 m/s.

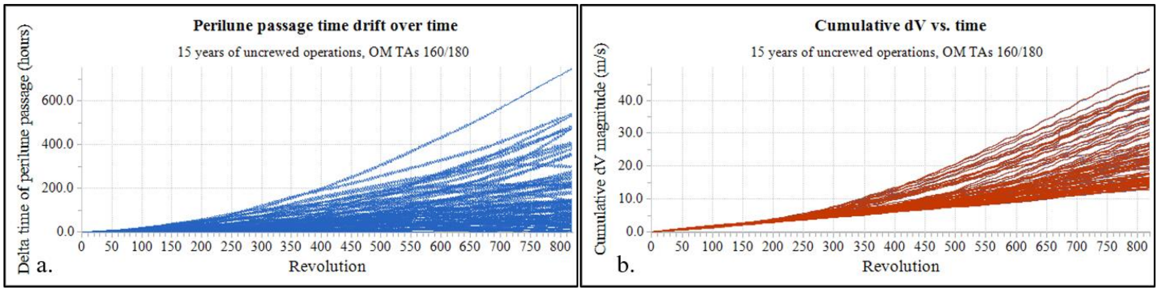

Figure 7. Perilune passage time drift (a) and cumulative Δv over time for 100 Monte Carlo trials over 15 years

Augmented short-horizon orbit maintenance maneuvers: targeting v_x and t_p

Over long simulations, the drifts in position and timing from the reference orbit increase and can lead to increased orbit maintenance costs and long eclipses. This drift can be managed by periodically regenerating a new, eclipse-free baseline NRHO, or it can be managed by phase control throughout operations. A simple, low-cost algorithm is identified to control the drift in perilune passage time along with v_x. The selected method, which employs a single burn each revolution, demonstrates the best performance out of a long list of algorithms examined in the current study; other candidate algorithms target various parameters along the baseline NRHO employing both single and multiple burns each revolution. The selected phase control algorithm augments the simple v_x targeting scheme by adding a weighted targeting of perilune passage time, t_p, every other revolution. The weighting is implemented by defining a target epoch

$$t_{targ} = W_t(t_{pref} - t_p) + t_p \tag{2}$$

where W_t = 0.3 is a weighting factor, t_{pref} is the perilune passage time along the baseline NRHO, and t_p is the perilune passage time achieved by the maintained spacecraft. The targeting of t_p is better achieved when the maneuver is not applied precisely at apolune; a parametric study concludes that setting TA = 160° achieves lower costs and improved algorithm reliability. The augmented algorithm is then summarized as follows:

- Even Revolutions: Execute v_x targeting
  - Step spacecraft to apolune, TA = 180°
  - Target $v_x = v_{xref} \pm 0.45$ m/s at perilune 6.5 revolutions downstream (Eq. 1)
  - If convergence fails, reduce targeting horizon until convergence is achieved
  - If $|\Delta v| > 3$ cm/s, execute maneuver. Otherwise skip maneuver.
- Odd Revolutions: Augment algorithm to target v_x and t_p
  - Step spacecraft to TA = 160°
  - Target $v_x = v_{xref} \pm 0.45$ m/s at perilune 6.5 revolutions downstream (Eq. 1)
  - If convergence fails, reduce targeting horizon until convergence is achieved
  - Do not execute maneuver. Use computed Δv as an initial guess to target:
    - $v_x = v_{xref} \pm 0.45$ m/s (Eq. 1) **and**
    - $t_p = t_{targ} \pm 15$ minutes at perilune 6.5 revolutions downstream (Eq. 2)
  - If convergence fails, reduce targeting horizon until convergence is achieved
  - If $|\Delta v| > 3$ cm/s, execute maneuver. Otherwise skip maneuver.

Results from the augmented algorithm appear in Figure 5 on the right for 100 Monte Carlo trials, each representing three years of uncrewed operations in the NRHO, with errors applied as summarized in Table 2. The augmented algorithm effectively controls phase within the NRHO, as evidenced by the limited drift in perilune passage time appearing in Figure 5d: the times vary by less than an hour compared to the baseline, with no secular growth. Individual orbit maintenance burn magnitudes range from the minimum 3 cm/s to about 13 cm/s, as in Figure 5f. The mean annual orbit maintenance cost for the augmented algorithm is 1.0

m/s, representing a slight increase in cost over the original algorithm. Note that similar results are achieved by targeting v_x and t_p at TA = 160° every revolution rather than following the every-other-revolution strategy outlined above.

The burn directions associated with the augmented algorithm fall into two categories. First, the burns applied on even revolutions at TA = 180° targeting v_x only are directed generally along the positive or negative stable mode direction, as observed in the simple algorithm and pictured in Figure 6a-c. The burns on odd revolutions at TA = 160° targeting both v_x and t_p demonstrate a less distinct pattern; however, they are not random. The rotating *x*, *y*, and *z* unit vector components of these burns appear in Figure 6d for 100 Monte Carlo trials, each 56 revolutions (1 year) in duration. The burn directions and locations are plotted in 3D in the Earth-Moon rotating frame in Figure 6e. Many of the burns include a significant out-of-plane component. The patterns are most evident when the unit vector itself is plotted, as in Figure 6f. All of the burns lie in a plane, with the unit vectors arranged like spokes in a bicycle wheel.

Sensitivity to assumptions

The simulations thus far assume that errors acting on the spacecraft are modeled as described in the Table 2 baseline column. However, the Gateway spacecraft is still under development, and as it is constructed, assumptions and spacecraft characteristics will likely change. The sensitivity to errors is explored to assess the robustness of the algorithm as well as potential variation in costs. In each case, one of the error models is varied while the others remain fixed at their baseline levels.

Earlier studies predict an approximately linear relationship between OM cost and navigation errors.[6] The same general trend is present in the augmented algorithm. Navigation errors ranging from 0.1 km in position and 0.1 cm/s in velocity (3σ), the levels achieved by the ARTEMIS mission,[8] up to a maximum of 20 km in position and 20 cm/s (3σ) are considered. The minimum, mean, and maximum annual OM Δv appear in Figure 8a. Mean annual costs range from just under 1 m/s to 4.3 m/s.

The number of desaturations required to maintain attitude as the spacecraft experiences torques from the gravity gradient near perilune depends on the characteristics of the reaction wheel assembly as well as the moments of inertia of the spacecraft, which will vary as the Gateway is constructed. Since the NRHO is sensitive to perturbations near perilune, increasing the number of desaturations near the Moon also increases cost, as is apparent in Figure 8b. The mean annual cost of 0.7 m/s, achieved when no desaturations are needed near perilune, increases to 1.2 m/s if the spacecraft must dump momentum 7 times over perilune. Similarly, the translational Δv resulting from each desaturation affects the annual cost, with larger perturbations of course correlating to larger OM requirements, as in Figure 8c. When the translational Δv resulting from the desaturation burn is a small value (0.1 cm/s, 3σ), the mean annual cost is again 0.7 m/s, as when no desaturation burns are performed near perilune. If the 3σ perturbation from each desaturation maneuver is increased to 4 cm/s, the stationkeeping cost averages 3.1 m/s per year.

Finally, it is noted that the baseline NRHO does not include solar pressure force in the modeling, since little was known about the Gateway structure when the baseline was generated. However, SRP is included in the simulations in the current study. Because the baseline is simply used as a catalog of values of v_x and t_p at perilune, the lack SRP force modeling in the baseline does not significantly affect cost as long as the area to mass ratio remains relatively small. The annual cost as a function of this ratio appear in Figure 8d; the maximum anticipated ratio is expected when the Gateway consists only of solar panels and a power and propulsion bus, with area/mass ~ 0.05 m^2/kg. For this value and under, the lack of SRP in the baseline does not appear to have a significant effect on mean annual cost.

Maneuver execution errors are also explored. In one-year simulations that vary maneuver execution errors from one tenth of their baseline value up to 2.5 times their baseline value, no significant effect on the annual cost is observed. It is noted that for a 15-year simulation considering the large errors from Table 2, an increase in annual cost of about 0.4 m/s is observed when the execution errors are doubled.

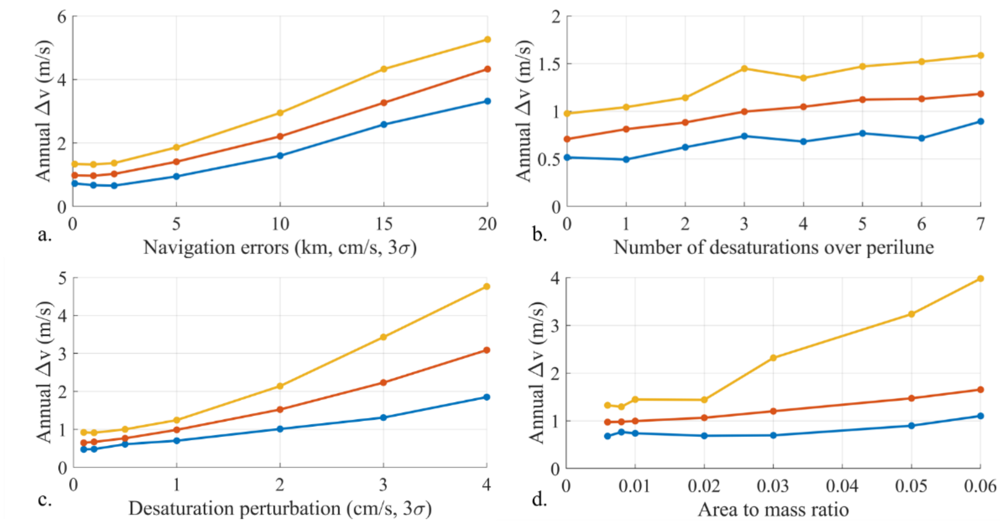

Figure 8. Minimum, mean, and maximum annual Δ*v* varying navigation errors (a), desaturation perturbation (b), number of desaturation (c), and SRP area to mass ratio (d)

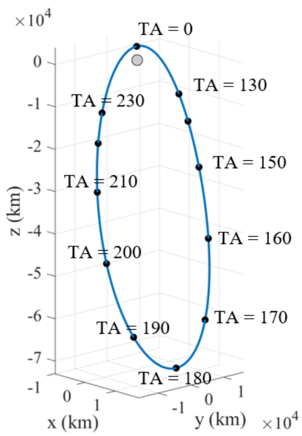

Figure 9. TA in the NRHO

The placement of the OM burns also affects the total cost. The NRHO is highly sensitive near perilune, so burns near the Moon magnify orbit determination and maneuver execution errors. In the presence of such errors, maneuvers near apolune are the least costly. Although the NRHO is a non-Keplerian orbit, the TA remains an intuitive measure of placement along the orbit. In the current study, TA is computed as an instantaneous osculating orbital element. The best maneuver TA location depends on the error models applied in a given simulation as well as burn type. For burns targeting only v_x, maneuvers with TA < 160° and TA > 190° are associated with algorithm failure; burns with 165° < TA < 185° yield the best performance for baseline errors. Effects are small in this range; over a 15-year lifetime, a total improvement of less than half a meter per second is observed by moving the v_x targeting burn from TA = 180° to TA = 170°. For burns targeting both v_x and t_p, maneuver placement directly at apolune is ineffective; a resonant and increasing pattern is induced in the position errors, and the algorithm fails after several years in the simulation. Placing the v_x and t_p targeting burn at TA = 160° yields the best observed performance. If it is desired or necessary to place the burn after apolune, a maneuver location at TA = 200° achieves similar results.

Gateway lifetime analysis

The Gateway is planned to support crewed exploration beyond Earth orbit for 15 years or more. The augmented orbit maintenance algorithm is, thus, simulated for 15 years to verify the long-term behavior of the spacecraft in the presence of errors. In the current investigation, only uncrewed operations are simulated; in reality, a crew visit to the Gateway and the lunar surface is expected about once a year, bringing additional perturbations. Additionally, a single Gateway configuration is assumed for the full 15-year simulation; as the Gateway is constructed over time, the spacecraft will exist in a variety of different configurations necessitating changes in error models. However, the simplified scenario yields an understanding of long-term behavior of the orbit maintenance algorithm.

Assuming baseline errors acting on the spacecraft as summarized in Table 2, 100 Monte Carlo trials are run, each spanning 820 revolutions in the NRHO, or about 15 years. Results of the simulation appear in Figure 10. The cumulative Δ*v* appears in Figure 10a for each of the trials. Total cost for orbit maintenance for the 15-year simulation ranges from 13.5 m/s to 17.5 m/s, with a mean annual Δ*v* of 1 m/s. The individual OM burn magnitudes appear in Figure 10b. The maneuvers range in size from 3 cm/s to about 15 cm/s. The drift in perilune passage time relative to the baseline NRHO appears in Figure 10c. Over the 15-year propagation, variations in t_p as compared to the baseline remain under an hour. Similarly, the drift in *x*, *y*, and

z position components measured at perilune remain under 75 km each and do not grow over time, as is apparent in Figure 10d. All 100 Monte Carlo trials represented in Figure 10 successfully complete the full 15 years of targeting; in fact, not a single maneuver reduces the targeting horizon from 6.5 revolutions to a smaller value to aid in convergence. The augmented OM algorithm effectively maintains the spacecraft in NRHO for 15 years given the assumptions in Table 2.

Two bounding cases are explored to assess the effects of changing error assumptions; the first is a simulation representing "worst case" large errors as specified in Table 2. Large navigation errors, frequent large desaturations near perilune, and larger maneuver execution errors all contribute to higher costs, as does a relatively large area to mass ratio of 0.05 m^2/kg, which exacerbates the effects of SRP missing from the baseline NRHO. The cumulative Δv over the 15-year lifespan appears in Figure 11a. The total averages about 58 m/s, yielding an annual Δv of about 4 m/s. Approximately once per trial, the targeter is unable to converge with a 6.5 revolution targeting horizon and steps back to a 4.5 revolution targeting horizon. Every Monte Carlo trial successfully completes the full 15 years of orbit maintenance with the large error assumptions. Similarly, small errors assume a "best case" scenario, again detailed in Table 2. Small navigation errors of 0.1 km in position and 0.1 cm/s in velocity are similar to those achieved by ARTEMIS.[8] No desaturations are assumed over perilune, and the area to mass ratio is small. The cumulative OM cost appears in Figure 11b. The costs total about 6 m/s over the 15-year simulation, with a mean annual cost of 0.4 m/s.

A summary of the minimum, mean, and maximum annual OM costs for simulations of different durations and error models appears in Table 3. Note that when phase control is included, the one-year simulations yield a similar annual cost compared to the long, 15-year simulations: the added duration of the simulation only slightly increases the annual cost, and the variation in the annual cost decreases. Without phase control, however, the annual cost of the 15-year simulation varies significantly. Though the 1-year cost without phase control is slightly lower than the 1-year cost including phase control, over the 15-year lifetime, the annual cost is improved when phase control is included in orbit maintenance.

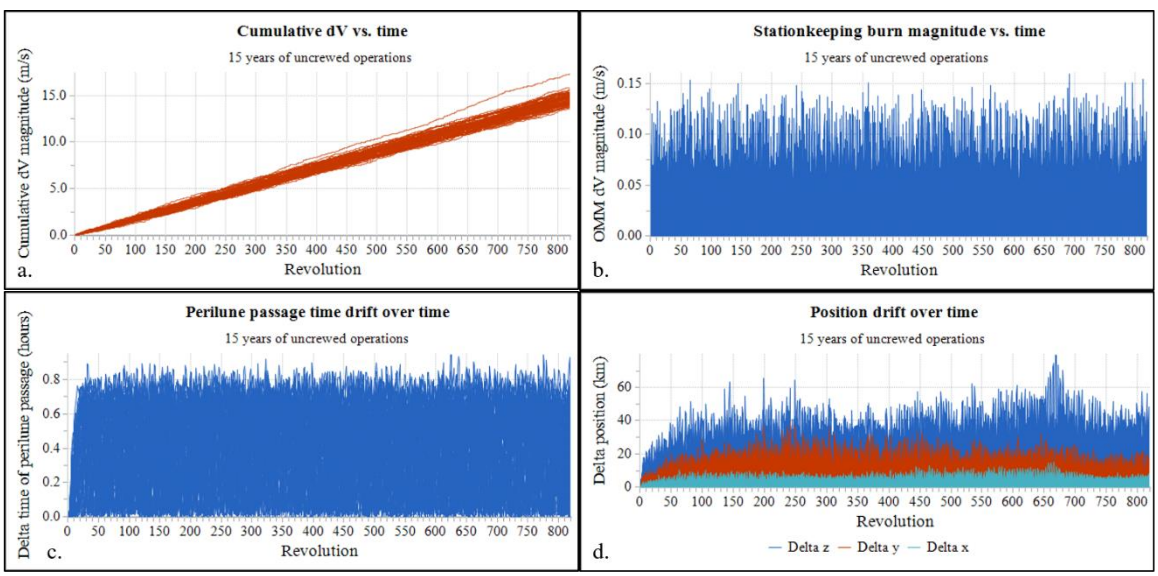

Figure 10. 15-year Monte Carlo Simulation results: baseline errors, uncrewed operations

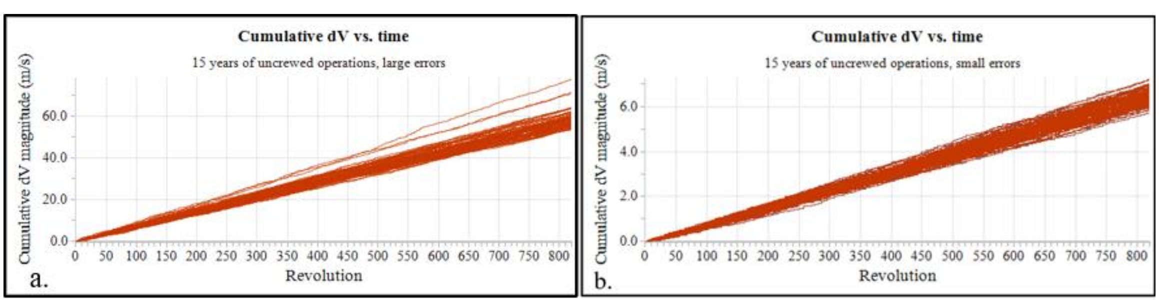

Figure 11. 15-year cumulative Δv considering large (a) and small (b) error models

The current study focuses on uncrewed operations within the NRHO, with a fixed area to mass ratio throughout the spacecraft lifetime. In reality, the Gateway structure will grow over time, with a maximum area to mass ratio of about 0.05 m^2/kg present at the beginning of operations. The ratio will decrease over time as mass is added, since but the solar panels will continue to represent the majority of the sun-facing area of the structure. The arrival of Gateway elements and logistics modules add perturbations associated with docking and undocking. Additionally, a crewed visit by Orion in support of human lander missions is expected annually. Perturbations include venting from Orion, additional RCS events, and further docking and undocking disturbances.[10] These perturbations add to the total orbit maintenance cost over time. While simulations of the crewed missions to Gateway are not yet included in the current study, an analysis shows that adding a significant disturbance to the orbit once per year increases the OM cost without causing failure in the algorithm. An impulsive maneuver is applied at apolune in either the velocity direction, the normal direction, or the binormal direction every 56 revolutions to simulate a large perturbation. The OM algorithm continues to converge for all tested cases, including maneuvers from 1-4 m/s in magnitude.

Table 3. Minimum, mean and maximum OM cost for various simulations of uncrewed operations

			annual Δv (m/s)				
years	phase control?	errors	min	mean	max	failures	trials
1	no	baseline	0.63	0.87	1.18	0	100
3	no	baseline	0.74	0.89	1.07	0	100
15	no	baseline	0.84	1.54	3.37	0	200
1	yes	baseline	0.65	0.98	1.45	0	600
3	yes	baseline	0.83	1.00	1.21	0	100
15	yes	baseline	0.92	1.00	1.18	0	100
1	yes	small	0.25	0.38	0.52	0	200
3	yes	small	0.34	0.40	0.51	0	100
15	yes	small	0.39	0.44	0.49	0	200
1	yes	large	2.73	4.03	7.67	0	200
3	yes	large	3.37	3.99	6.91	0	100
15	yes	large	3.64	3.99	5.28	0	100

Long-horizon Retargeting Maneuvers

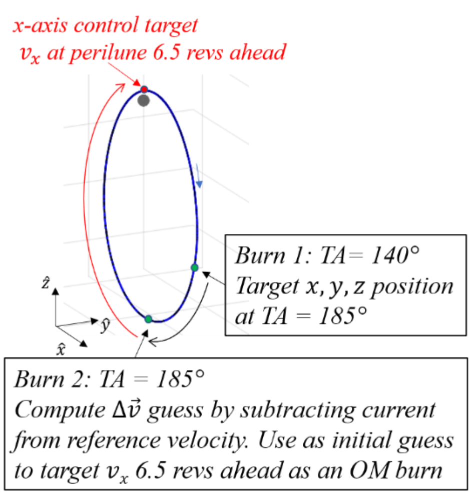

Figure 12. Retargeting maneuver

In response to large or unexpected perturbations, the spacecraft may begin to drift from the long-horizon reference orbit, even when phase control is included. Such a drift causes the orbit maintenance costs to grow, since the spacecraft diverges from the ballistic baseline NRHO that provides the stationkeeping targets. Thus, it may become necessary to either regenerate a new long-horizon NRHO from the current state or execute a series of maneuvers to retarget the reference trajectory. In the current study, a two-maneuver transfer is designed to rendezvous with the original reference orbit. The two burns appear in a schematic in Figure 12. The first burn is placed at TA = 140° and is designed to achieve a set of weighted x, y, and z position targets derived from the baseline NRHO just after apolune at TA = 185°. The targets are computed such that

$$
\begin{aligned}
x_{target} &= W_x(x_{ref} - x) + x \\
y_{target} &= W_x(y_{ref} - y) + y \\
z_{target} &= W_x(z_{ref} - z) + z
\end{aligned}
\tag{3}
$$

where $W_x = 0.3$ is a weighting factor, x_{ref}, y_{ref}, and z_{ref} are the position components along the baseline NRHO, and x, y, and z are the position components achieved by the maintained spacecraft. At this point, the second burn is designed by first computing the Δv required to rendezvous with the baseline orbit; that is, the difference between the Gateway velocity and the baseline NRHO velocity. This Δv provides an initial guess to design an orbit maintenance burn, targeting v_x at perilune 6.5 revolutions downstream. If each burn exceeds the 3 cm/s minimum maneuver threshold, the maneuver pair is executed. Otherwise, neither burn takes place. The two-burn retargeting scheme can, thus, be summarized as follows:

- Step spacecraft to TA = 140°
- Compute Δv_1 to target $x = x_{target} \pm 10$ km, $y = y_{target} \pm 10$ km, and $z = z_{target} \pm 10$ km at TA = 185°
- Step spacecraft to TA = 185°
- Compute $\Delta v_{guess} = v_{ref} - v$ at current location.
- With computed Δv_{guess} as an initial guess, compute Δv_2 to target $v_x = v_{xref} \pm 0.45$ m/s (Eq. 1) 6.5 revolutions downstream
- If $|\Delta v_1| > 3$ cm/s and $|\Delta v_2| > 3$ cm/s, execute maneuvers. Otherwise skip maneuvers.

The retargeting maneuver pair can be executed when the drift in position, velocity, or perilune passage time reaches a certain threshold, or it can be executed on a schedule, for example, after a crew visit. The retargeting maneuvers effectively restore the spacecraft to NRHO in the presence of certain large perturbations.

CONCLUDING REMARKS

The Gateway baseline NRHO successfully avoids eclipses longer than 80 minutes for at least 15 years. Previous orbit maintenance algorithms yield robust, low-cost, long-term stationkeeping by targeting v_x along a baseline virtual reference. However, without phase control, the spacecraft drifts from the baseline, and the eclipse-free characteristics of the baseline trajectory are lost. The current study updates the x-axis crossing control algorithm to additionally maintain the eclipse-free phase. By adding a second target, t_p, on alternating revolutions, the phase is maintained without reduction in robustness or significant cost increases. The orbit and phase are successfully maintained over 15-year simulations, avoiding long eclipses from the Earth's shadow. In addition, a strategy to retarget the long-horizon reference trajectory is developed.

The current study considers only uncrewed operations in the Gateway. A preliminary analysis of significant large annual perturbations suggests that the algorithm will also yield robust results in a higher fidelity analysis that includes crewed missions each year. Future analysis will confirm this assumption.

ACKNOWLEDGEMENTS

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