National Aeronautics and Space Administration (NASA)

White Paper:
Gateway Destination Orbit Model:
A Continuous 15 Year NRHO Reference Trajectory

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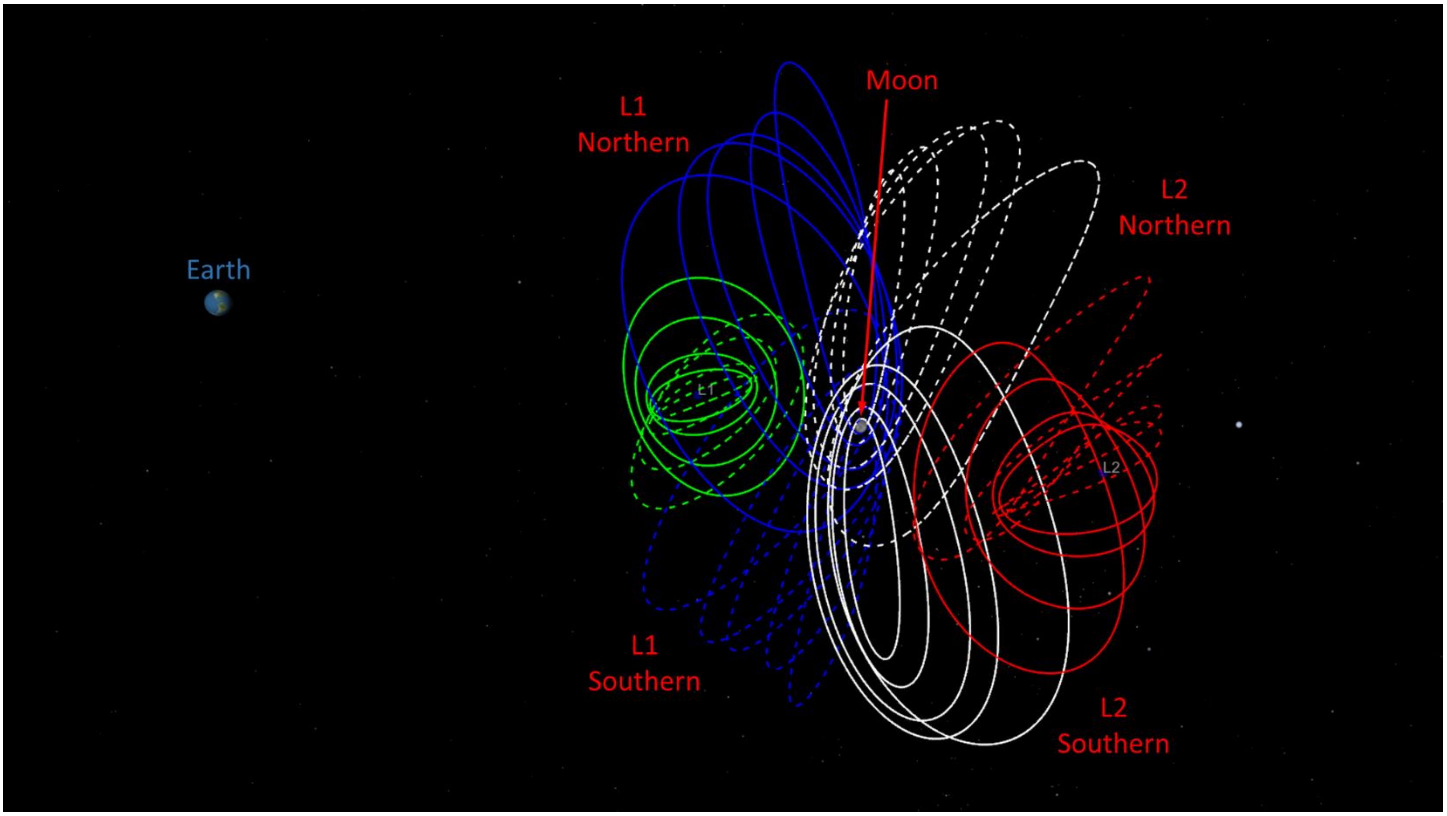

Figure 1: Halo Orbit Families

Introduction

The Gateway program has selected a Near-Rectilinear Halo Orbit (NRHO) of the L_2 southern family as its operational orbit [1]. In order to facilitate mission analysis for Gateway and associated programs utilizing this orbit, a representative reference trajectory 15 years in duration has been developed. The purpose of this white paper is to review the properties of this NRHO reference trajectory.

Background: Selection of NRHO as Gateway Orbit

Suitability of NRHOs for Gateway

NRHOs are a subset of the halo orbits, a class of orbits that exist in three body systems (i.e. systems with two gravitational bodies, like the Earth-Moon system) [2]. There are halo orbits associated with all three collinear libration points [3], however only those in the vicinity of the libration points nearest the Moon (L_1 and L_2) are of interest for the present discussion. For both L_1 and L_2, there are also northern and southern families of NRHOs, which mirror each other about the Earth-Moon orbit plane [4]. Figure 1 illustrates the four families of halo orbits near the Moon: the L_1 northern, L_1 southern, L_2 northern, and L_2 southern families.

The NRHOs are set apart from the rest of the halo orbits by their favorable stability characteristics [4] [5] [6]. They exist at the end of the halo orbit range with the lowest perilune radii [4]. Viewed in the rotating frame, "the NRHOs are characterized by an elongated shape that resembles an ellipse" [5], but they cannot be approximated as two-body Keplerian orbits.

In general, NRHOs were selected as the orbit for Gateway because they represent an advantageous staging orbit in which to aggregate resources for a variety of potential mission objectives. They have neutral stability characteristics, and therefore low orbit maintenance costs [4] [6] [7]. These orbits are accessible to Orion within the capability of the existing Service Module [8] [9], and they offer access to the lunar surface with relatively short trip times of about 0.5 days [8]. Cargo can be delivered to the NRHO via four-body Ballistic Lunar Transfers (BLTs) with very low ΔV requirements [9] [10]. It is possible to depart for interplanetary destinations from the NRHO [11]. Also, they provide extended periods of communications coverage to one of the lunar poles, with only short blackouts [8] [12].

Selection of the Specific Orbit

The particular orbit selected for Gateway is an NRHO of the L_2 southern family with an orbit period selected for a 9:2 Lunar Synodic Resonance (LSR) and phasing set for

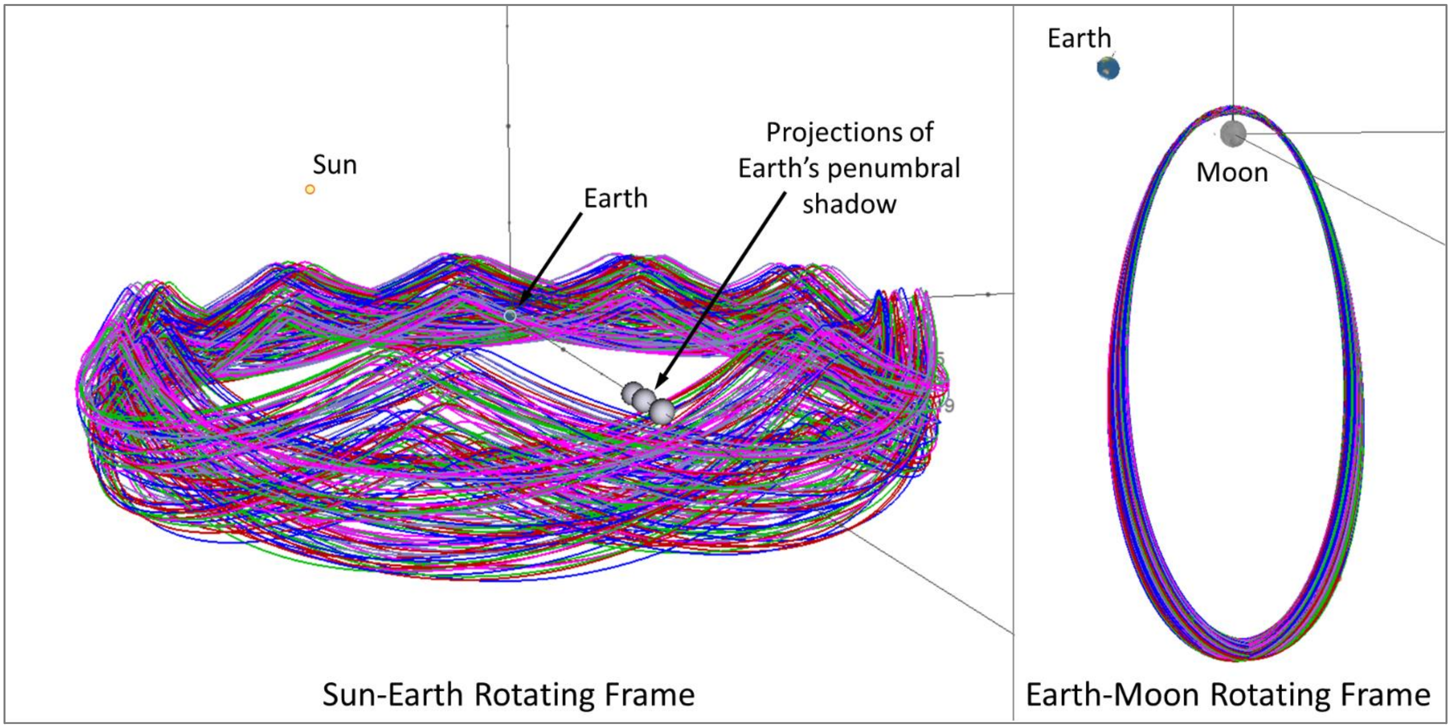

Figure 2: 15 Year NRHO Reference Trajectory. The figure on the left shows the trajectory in the Earth-centered Sun-Earth rotating frame, illustrating the 9:2 LSR pattern for eclipse avoidance. The figure on the right shows the trajectory in the familiar Moon-centered Earth-Moon rotating frame.

avoidance of eclipses by the Earth [1]. The selection of this specific orbit was based on several criteria.

An L_2 family NRHO was initially selected because of better visibility to the lunar far side for communications [8]. Additionally, the L_2 NRHOs in the range of interest have better stability characteristics compared to L_1 NRHOs in a similar range, leading to lower orbit maintenance requirements in propellant and ΔV [4] [6].

A southern family NRHO was selected because this offers lower ΔV and propellant requirements for Orion returning from the NRHO. This is due to the geometry of returning to a splashdown in Earth's northern hemisphere. The southern family also has the advantage of very good communications coverage to the surface for sites near the lunar south pole [8] [12], which is currently a region of interest [13] [14].

An NRHO with a Lunar Synodic Resonant (LSR) period was deemed desirable as it offered the possibility of avoiding eclipses, particularly eclipses by the Earth [15], which can have durations well in excess of current hardware limits for the Gateway and Orion spacecraft. (More on this later.) Both 4:1 and 9:2 LSR cases were considered. The 9:2 LSR NRHO was ultimately selected because it offered a relatively low perilune radius [15], which is advantageous for surface access [9].

Characteristics of the Reference Trajectory

The Gateway NRHO reference trajectory is captured in a SPK-type kernel compatible with the SPICE ephemeris system created at the NASA Jet Propulsion Laboratory (JPL) [16]. (SPICE SPK-type kernels are binary files which store ephemeris data [17].) The full trajectory kernel is available on the JPL website [18].

The reference trajectory represents an orbit with the characteristics already described for Gateway: an NRHO of the L_2 southern family with an orbit period selected for a 9:2 Lunar Synodic Resonance and phasing set for avoidance of eclipses by the Earth.

The Gateway NRHO reference trajectory spans 15 years, from January 2, 2020 to February 11, 2035. The trajectory is continuous in position, with small velocity adjustments (or discontinuities) occurring every NRHO rev near apolune. These adjustments are necessary to maintain the stability of the NRHO in the ephemeris gravity model. The adjustments are quite small, with an average magnitude of only 1.86 mm/s per NRHO rev.

It's important to note that this is an idealized reference trajectory, intended to be generic to the particulars of specific spacecraft and mission designs. The only perturbations considered are those from the n-body gravitation model in the ephemeris. No other perturbations or errors were considered: no solar

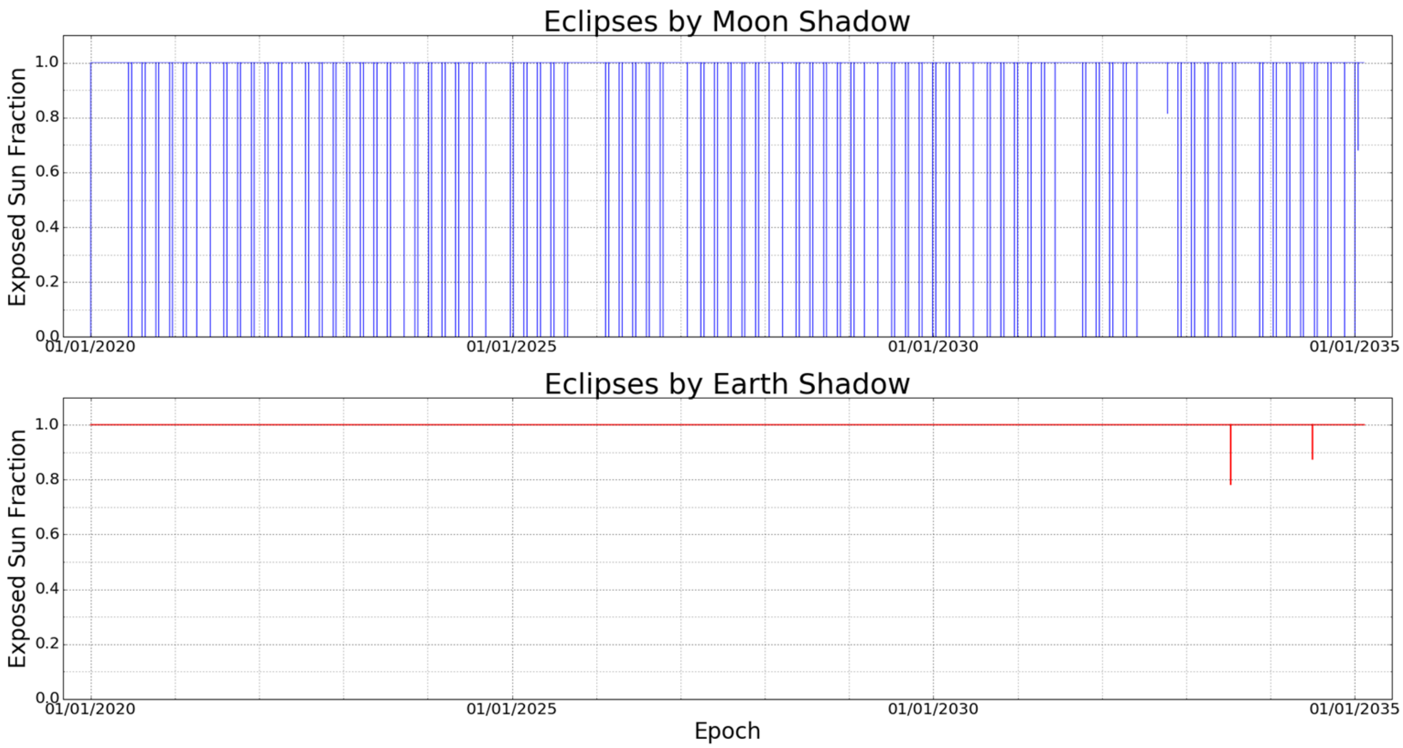

Figure 3: Eclipse History for NRHO Reference Trajectory.

pressure, no drag, no spacecraft noise, no navigational errors, no insertion errors, etc. The velocity adjustments are small compared to the additional errors and perturbations that would typically be expected for an actual spacecraft, and also when compared to the actual correction maneuvers that would be required to maintain the orbit [4] [6].

Also, no active phase control was applied in the generation of the trajectory. It is a "natural" trajectory, in that sense, and accomplishes eclipse avoidance by virtue of a judicious selection of initial conditions only.

Figure 2 shows the reference trajectory displayed in two frames: an Earth-Centered Sun-Earth rotating frame, and a Moon-centered Earth-Moon rotating frame. In the Earth-Moon rotating frame, on the right, we can see the familiar NRHO shape, albeit with 15 years of variations.

In the Sun-Earth rotating frame, on the left, we can see how the LSR orbit accomplishes eclipse avoidance: by setting up a repeating geometrical pattern in the Sun-Earth frame, which consistently avoids passing through the Earth's shadow (along the axis opposite the Sun). Note that the elliptical shapes on this axis are projections of the Earth's outer shadow, or penumbra.

The 9:2 Lunar Synodic Resonance indicates that the orbit will make, on average, 9 revolutions for every 2 lunar months. The resulting orbit has a perilune radius that varies from 3196 to 3557 km, with an average of 3366 km. The average orbit period of the reference trajectory is 6.562 days, closely matching the value that would be expected by applying the resonance ratio to the mean lunar synodic period.

Avoiding eclipses by the Earth was a primary design goal for this reference trajectory, as these eclipses can approach 5 hours in overall duration, and include periods of total eclipse of over 2.6 hours, durations well beyond current hardware limits for the Gateway and Orion spacecraft. The reference trajectory is successful in avoiding eclipses by the Earth, with the exception of two grazing partial eclipses during the 14th and 15th years. (See Figure 3.) It is actually expected that a new reference trajectory would be developed before this point.

Eclipses by the Moon, while relatively frequent with several occurring every year, are always less than 80 minutes in duration, within current hardware limits.

If Gateway were not utilizing an LSR orbit for eclipse avoidance, occasional eclipse avoidance maneuvers would be required, and Gateway operations would require ongoing predictions of future eclipse risks. These avoidance maneuvers would have some finite propellant cost, and they would also complicate operations and mission planning.

Using an LSR NRHO with built-in eclipse avoidance, the Gateway program needs only incorporate phase control into their orbit maintenance scheme to completely avoid eclipses by the Earth. Dedicated eclipse avoidance maneuvers are eliminated altogether, and mission planning, including assessing potential launch dates, can be performed years in advance with high confidence.

Because the 9 rev phase pattern spans 2 lunar months, there are two possible phasing options for eclipse avoidance in a 9:2 LSR NRHO. This reference trajectory follows the phasing slot selected by the Gateway program. While there is no particular reason to think either phasing option would offer an overall performance advantage, it was necessary to select a particular slot to ensure consistency. When new reference trajectories for Gateway are created, they must follow the same phasing slot in order to be compatible with a transition between reference trajectories, and to preserve the validity of previous mission planning and analysis work.

It may be worth noting that if a satellite with the requisite communications gear were placed in the alternative phasing slot, the combination of that satellite with the Gateway could provide continuous communications with sites near the lunar south pole. [12].

Another potential application of the reference trajectory is as a reference for control algorithms for orbit maintenance and phase control. State data can be extracted to serve as a reference for orbit maintenance targeting, and timing data as a reference for phase control [4] [6].

Methodology and Force Model

Methodology for Generating the Trajectory

The reference trajectory was developed by means of an iterative process, involving the successive generation of a series of candidate trajectories with unique initial conditions, each of which was evaluated for avoidance of eclipses by the Earth. Each candidate trajectory was generated as follows:

An initial "seed" trajectory 27 revs in duration was generated for a given perilune radius and set of initial conditions. The seed trajectory was generated using a multiple shooting method with a differential correction solver in the ephemeris, starting from patch points developed in a circular restricted three body problem model. The duration of NRHO trajectories which can be generated using this method is limited to several months, however, so another method was required for an extended duration reference trajectory. [15]

The initial epoch and state were then taken from the converged seed trajectory, and used to initiate a receding horizon targeting process. The receding horizon targeting method starts from a converged or nearly converged initial state, and solves for a very small velocity change in order to achieve a target condition of $v_x = 0$ at the X-Z plane crossing near perilune several revs later (in an Earth-Moon two-body rotating frame) [15]. This targeting process was repeated every NRHO rev, with velocity adjustments applied every rev near apolune. In this case, the target perilune was 11 revs from the initial state, and 10.5 revs from the velocity adjustment. This process allowed the generation of NRHO trajectories with durations of several years [15].

In order to achieve long-term avoidance of eclipses by the Earth, the initial conditions were adjusted, and the process repeated until an adequate duration of eclipse avoidance had been obtained and/or longer durations of eclipse avoidance became difficult to achieve.

Force Model and Propagation

The force model used in propagating the reference trajectory used only n-body gravitation. No other perturbing forces were considered. Four gravitational bodies were included: the Earth, the Moon, the Sun, and the Jupiter Barycenter.

The DE430 ephemeris from JPL [19] was used to calculate the positions of the gravitational bodies. Planetary masses were taken from the DE431 ephemeris [19].

The Moon was treated as the central body. A spherical harmonic model of lunar gravity was utilized, the GRGM660PRIM model [20], with both degree and order of 8 (i.e. 8 x 8).

The trajectory was propagated using the DDEABM integrator, a "variable step size, variable order Adams-Bashforth-Moulton PECE solver for integrating a system of first order ordinary differential equations" [21] [22], with both relative and absolute tolerances set to 1.0e-13.

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