Title

Cislunar Near Rectilinear Halo Orbits for Human Space Exploration

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Extended Abstract

In order to conduct sustained human exploration beyond Low Earth Orbit (LEO), spacecraft systems are designed to operate in a series of missions of increasing complexity. Regardless of the destination, Moon, Mars, asteroids or beyond, there is a substantial set of common objectives that must be met. Many orbit characterization studies have endeavored to evaluate the potential locations in cislunar space that are favorable for meeting common human exploration objectives in a stepwise approach. Multiple studies, by both NASA and other international space agencies, have indicated that Earth-moon libration point orbits are attractive candidates for staging operations in the proving ground and beyond.

In particular, the Near Rectilinear Orbit (NRO) has been demonstrated to meet multi-mission and multi-destination architectural constraints. However, a human mission to a selected NRO presents a variety of new challenges for mission planning. While a growing number of robotic missions have completed successful operations to various specific libration point orbits, human missions have never been conducted to orbits of this class. Human missions have unique challenges that differ significantly from robotic missions, including a lower tolerance for mission risk and additional operational constraints that are associated only with human spacecraft. In addition, neither robotic nor human missions have been operated in the NRO regime specifically, and NROs exhibit dynamical characteristics that can differ significantly as compared to other halo orbits. Finally, multi-body orbits, such as libration point orbits, are identified to exist in a simplified orbit model known as the Circular Restricted Three Body Problem (CRTBP) and must then be re-solved in the full ephemeris model. As a result, the behavior of multi-body orbits cannot be effectively characterized within the classical two-body orbit dynamics framework more familiar to the human spaceflight community. In fact, a given NRO is not identified by a set of Keplerian orbit parameters, and a valid epoch specific state vector must be first obtained from a multibody dynamical model.

In this paper, the significant performance and operational challenges of conducting human missions to the NRO are evaluated. First, a systematic process for generating full ephemeris based ballistic NROs of various families is outlined to demonstrate the relative ease in which a multi-revolution orbit can be found for any epoch and

for various orbit geometries. In the Earth-Moon system, NROs, which are halo orbits with close passage over a lunar pole, can exist with respect to libration point 1 (L1) or libration point 2 (L2) and are either from a North or South family orbit class with respect to the ecliptic. Figure 1 displays the resultant four orbit classes.

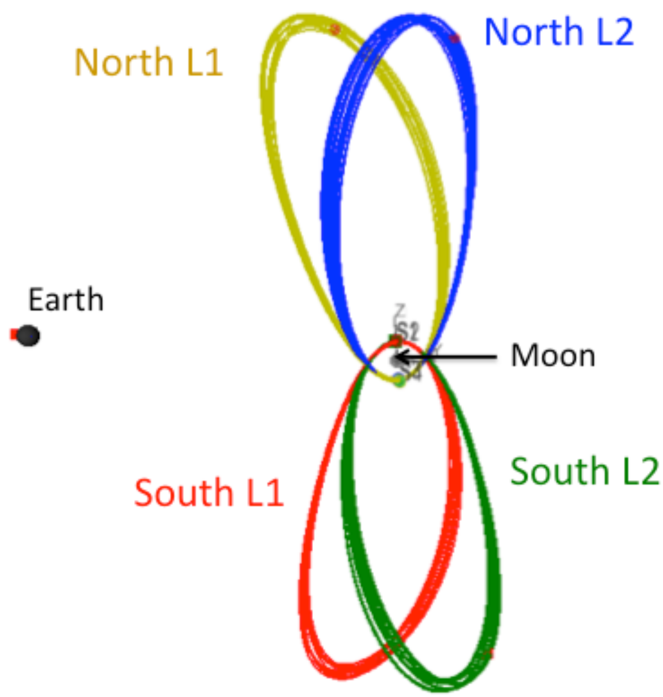

Figure 1: Four NRO Orbit Types: multiple revolutions in a rotating Earth-Moon frame.

Second, the ability to maintain the orbit over the lifetime of a habitat mission by applying a reliable stationkeeping strategy is investigated. The NRO, while similar to the quasi-halo orbits that the Artemis mission flew, requires an updated station keeping strategy. This is due to several dynamical differences such as the increased relative stability of the NRO compared to other halo orbits and the close passage over the lunar surface as shown in Figure 1. Multiple stationkeeping strategies are being investigated to ensure a human spacecraft remains on a predictable path. As the NRO is not described in simple two-body parameters, analysis must determine the best strategy for targeting a reference NRO as well as how closely a future state should be constrained. In addition, costs will be minimized by determining maneuver directionality based on an identified pattern in the optimal stationkeeping solutions or an analytically derived relationship. The candidate stationkeeping algorithm must be stable and robust to environmental and vehicle uncertainties as well to navigation estimation and flight control execution errors. To that end, navigation accuracies, the impact on the stationkeeping execution errors as well as other vehicle uncertainties need to be assessed. Starting with Orion, current navigation accuracies are evaluated and then navigation requirements are derived assuming a desired stationkeeping propellant budget. Third, the performance requirements to and from the NRO are evaluated. Important parameters for developing expected propellant costs include epoch of operation, size and type of NRO, Earth departure and return constraints, as well as abort or early-return capability. Finally, rendezvous and proximity operations are vital aspects of multi-mission human exploration endeavors. The ability to conduct rendezvous and the associated propellant costs are assessed as well as the impacts of various profile assumptions including the location within the NRO the rendezvous is performed. The results of these studies will influence plans for international cooperation on both nearer term proving ground missions and beyond.