EARTH-MOON L_2 TO MARS ROUNDTRIP TRANSFERS LEVERAGING INVARIANT MANIFOLDS

D. C. Folta[1] and K.C. Howell[2], [1]NASA/GSFC, Greenbelt Md, 20771, Code 595, Navigation and Mission Design Branch, david.c.folta@nasa.gov, [2] Hsu Lo Professor of Aeronautical and Astronautical Engineering, Purdue University, School of Aeronautics and Astronautics, West Lafayette, Indiana 47907, howell@purdue.edu

Introduction: Trajectories from Earth to Mars rely exclusively on direct transfers using impulsive Delta-Vs (ΔVs) to create a Type I or II heliocentric Hohmann transfer. Our proposal specifies the application of invariant manifolds between secondary bodies in a Sun centered system. Our investigation extends current knowledge of dynamical systems and invariant manifolds with recent operational (demonstrated) knowledge and expertise of Earth-Moon (EM) libration orbits to formulate an innovative next step. This design process for transfers between EM L_2 and the Mars system meets robotic and human exploration goals [1-3].

Recent analysis and research has given the astrodyanmcis community new tools and operational experience in dealing with the flight of missions in multi-body regions. Past research has established theoretical (academics) approaches [4-7]. The research recommended herein combines past research, proven knowledge of Earth-Moon system stability and maintenance, and new tools to efficiently and accurately generate families of transfers between Earth and Mars.

This abstract addresses Challenge Area 2: "Innovative Exploration Approaches, specifically the particular interest in analyses of trajectories of Earth-Moon L2 to the Mars system, and return."

Justification: Additional flexibility for supply lines and other traffic to-and-from Mars needs to be considered. This proposed research aids the buildup of infrastructures in Earth-Moon space that can access both potential astrophysical observatories at Sun-Earth libration orbits as well as Sun-Mars libration orbits, Mars' moons, and Mars planetary deployments. Additionally applications for sample return (direct or off – Earth quarantine and aggregation), larger payload mass, communication and navigation nodes and human interactions will benefit.

We propose research investigations involving several approaches that consider baseline trades between delta-v and flight time. This includes familiar cyclers and other fundamental, well-known routes to Mars, and original less-explored options that will expand capabilities and contribute to a flexible architecture which is key to fully characterize the Earth-Mars space.

Invariant Manifold Usage: The use of invariant manifolds has been demonstrated by NASA/GSFC – Purdue University through its application to recent transfers in the multi-body mission support to achieve EM L_2 and L_1 insertion conditions for two spacecraft, see Figure 1 [8,9]. The design process involves the expressed usage of both numerical (perturbation theory and high fidelity modeling) along with Floquet methods to identify the all possible transfers including the optimal (minimum) ΔV transfer.

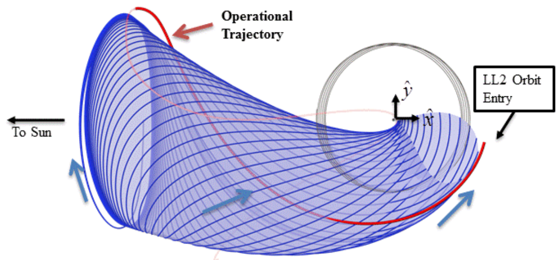

Figure 1. Sample Sun-Earth Invariant Manifold for Earth-Moon L_2 Insertion

Application to Earth-Mars Transfer Scenarios: The application to Earth Mars transfers begins with the correct modeling of the invariant manifold wrt the Earth –Moon system as shown in Figure 2. The transfer can exploit the Sun-Earth dynamical region, but the intent is not necessarily entry into a Sun-Earth libration orbit as that will extend the flight duration; rather, potentially passing through the Sun-Earth L_2 region to leverage the dynamical structure.

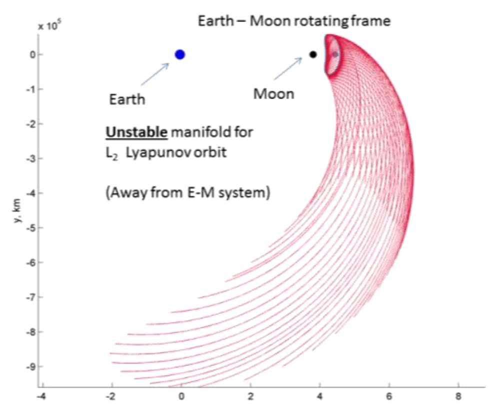

Figure 2. Departure Manifold from Earth-Moon L_2

Once the departure is achieved, the heliocentric orbit is not necessarily one that will transfer freely to Mars as demonstrated in Figure 3. Similar manifolds can also be generated for the Sun-Mars system, as shown in figure 4. The challenge of this process is to connect both stable and unstable manifolds for a minimal energy difference with minimal time durations. Durations may be relaxed for robotic missions; therefore all constraints must be separately controlled.

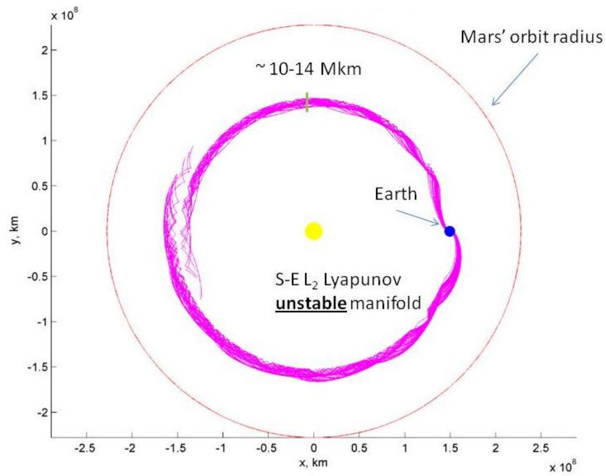

Figure 3. Earth Departure Heliocentric Manifolds

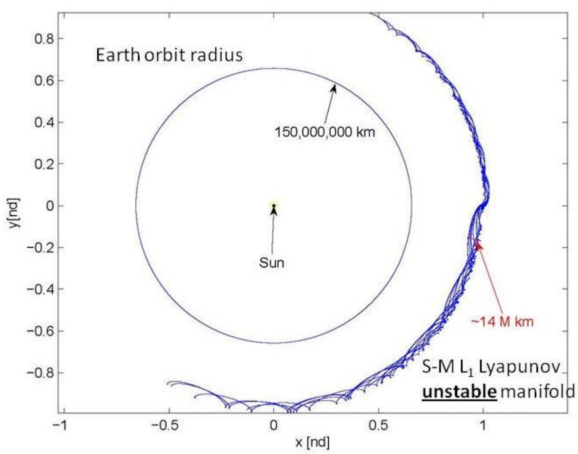

Figure 4. Mars Heliocentric Arrival Manifolds

Manifold Connections: To provide the optimal transfer trajectory for both to and from Mars, a unique tool developed by GSFC and Purdue called Adaptive Trajectory Design (ATD) can be utilized. This GUI tool provides the user with; the fundamental equations to determine the eigenstructure of both manifolds; the 'bridge' trajectories as required between arcs (manifolds or alternatives); the correction algorithms to merge the arcs; and the process to optimize the duration and ΔVs. The generation of all family members of the Earth – Mars invariant manifold and the optimization of the constraints can then be established.

Next Steps: The immediate goal is a complete exploration of the Earth-Mars space and the development of the capability to access a wide range of trajectory transfer alternatives. Ultimately, routes to-and-from Mars incorporating Earth-Moon libration points and invariant manifolds will play a role in long-term exploration plans. Therefore, an overall architecture must include some assessment of the interface between Sun-Earth, Earth-Moon, and Sun-Mars dynamical regimes. Adaptive strategies to efficiently design trajectories that seamlessly flow though these regions can be a foundation for both scientific and human-crewed missions.

The results of this process will enable NASA to quickly and efficiently generate all possible manifolds between Earth and Mars and enable the validation in numerical applications for direct usage in mission design proposals and operations. Once these transfers have been cataloged, orbital variations and contingencies can then be applied.

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