BepiColombo Gravitational Capture and the Elliptic Restricted Three-Body Problem

Stefano Campagnola*[1] and **Dr. Martin Lo**[2]

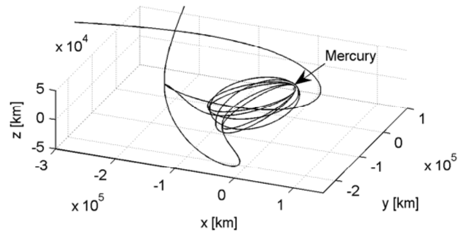
[1] Aerospace and Mechanical Engineering, University of Southern California, Los Angeles, CA 90089, USA
[2] Jet Propulsion Laboratory, Californian Institute of Technology, Pasadena , CA 01109, USA

This paper shows how the BepiColombo trajectory near Mercury follows the invariant manifolds to its final capture. The BepiColombo gravitational capture provides several recovery opportunities at nominal conditions and was designed by exploring the solution space entirely, without knowledge of the invariant manifolds. In this work we reproduced the trajectory in the model of the elliptic restricted three body- problem (due to the high eccentricity of Mercury's orbit) and showed that it does follow the manifolds. Consequently we envision that manifolds should be used to give insight on the solution space, speeding up the design and optimization process and there by saving cost.

1 Introduction

BepiColombo is the cornerstone ESA approved mission to Mercury. Two spacecraft will be launched jointly in 2013 and will reach their destination in 2019. The nearly 6-year long transfer includes several gravity assist and SEP (Solar Electric Propulsion, i.e. ion engines) thrust arcs[1].At Mercury a chemical burn (Mercury Orbit Insert MOI) inserts the spacecraft into a 400km x 12000 km polar orbit, with the line of apsides almost aligned with the Sun-Mercury eccentricity vector. To avoid a potential single point failure of a classical hyperbolic approach, an arrival scenario is implemented where the gravity of the Sun is exploited to weakly capture the spacecraft. This technique is called Gravitational Capture (GC).

Many GC trajectories can be found by simply varying the capture time and speed of the spacecraft, right before MOI. The first GC trajectory for BepiColombo was thus designed by exploring the solution space[2]. Initial conditions were propagated backward and forward with full ephemeris model. The trajectory which provided the best recovery opportunities was selected for the 2012 baseline[1] (Figure 1 on the left). In case of failure of the orbit insertion, there are three more MOI opportunities at almost nominal condition before the spacecraft eventually leaves Mercury's sphere of influence. This trajectory can be better understood in the frame of the spatial elliptic restricted three-body problem (ER3BP) due to the high eccentricity of Mercury's orbit. Figure 1 on the right shows the same GC computed in the ER3BP in the nondimensional pulsating frame where the primaries are at normalized and fixed positions. In the same reference frame we also plot the trajectory computed with real ephemeris.



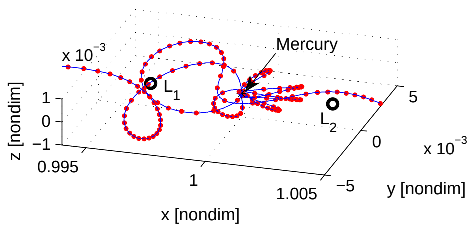


Fig. 1 Left: The BepiColombo gravitational capture in the Mercury equatorial reference frame. The trajectory was propagated with full ephemeris model. Right: The same trajectory is plotted in the pulsating reference frame (dotted line, one dot each day), where the Sun-Mercury vector is unitary and constant, aligned with the x-axis. The solid line is the trajectory computed in the ER3BP model.

2 BepiColombo and unstable orbits in the ER3BP

Unstable fixed points and periodic orbits and their stable and unstable manifolds play a key role in understanding any dynamical system[4]. For this reason we computed two quasi-periodic orbits and portions of their manifolds in the ER3BP, and compared such trajectories with the BepiColombo GC.

* Corresponding author: e-mail: scampagn@usc.edu, Phone: +1 210 713 9210, Fax: +1 210 713 7744
[1] In the last year the mission was redesigned for launch in 2013; the current GC is similar to the one studied here.

First we sought periodic and quasi-periodic orbits around the libration points. We expected GC trajectories to follow the stable manifolds of such orbits. In particular we computed a Lissajous orbit around L_1 with amplitude close to 4e-3 (by comparison with the BepiColombo GC). Figure 2 (left) shows the Lissajous orbit and a single trajectory on its stable manifold and a single trajectory on its unstable manifold.
We then looked at quasi-periodic around Mercury. We sought orbits with special symmetric features, allowing for several recovery options at nominal conditions. For this reason we required the quasi-periodic orbit to cross the syzygy axis perpendicularly when Mercury is at apohelium[3]. Figure 2 (center) shows the quasi-periodic orbit with trajectories from the stable and unstable manifolds which shadow the GC trajectory. Note the orbits from the manifolds are also symmetric.

Finally we compared the unstable orbits and their manifolds to the BepiColombo GC in Figure 2 (right). Coming from the interplanetary transfer, the spacecraft follows the stable manifold of the Lissajous and approaches L_1. After less then one revolution around the libration point, the trajectory shadows a heteroclinic connection between the Lissajous orbit and the quasi-periodic orbit around Mercury. In case the first MOI fails, the spacecraft continues to shadow the symmetric orbit and and will eventually escape Mercury's attraction along the unstable manifold after several MOI opportunities at nominal condition.

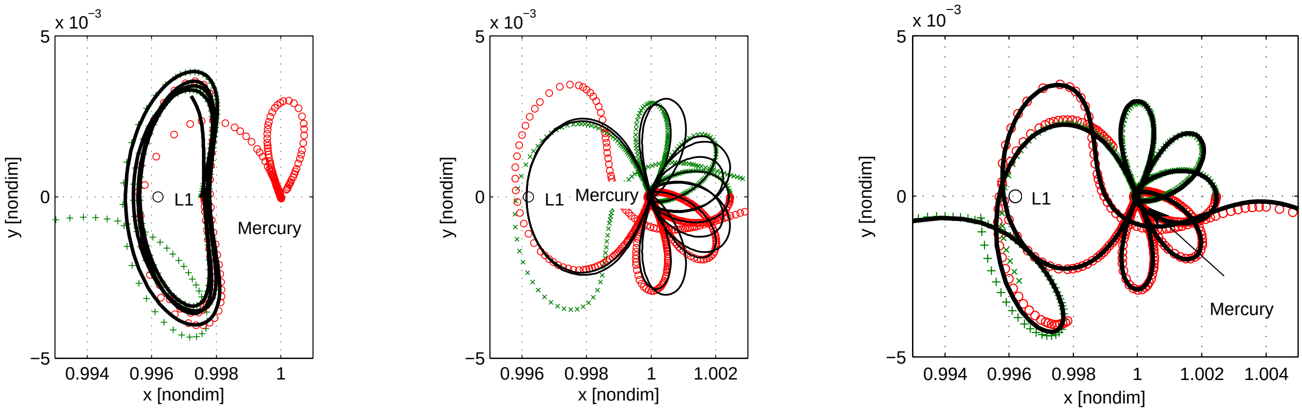


Fig. 2 Trajectories in the pulsating reference frame (projection onto the xy plane). Left: The Lissajous orbit is plotted together with one trajectory of the stable manifold (circle) and one trajectory of the unstable manifold (stars). Center: The symmetric quasi-periodic orbit around Mercury is plotted with one trajectory of the stable manifold (star) and one trajectory of the unstable manifold (circle). Note the manifolds are also symmetric. Right: The BepiColombo GC (solid line) shadows the stable and unstable manifolds.

3 Conclusions

We reproduced the BepiColombo trajectory in the model of the elliptic restricted three body problem, showing that it follows the stable and unstable manifolds of quasi-periodic orbits. In particular, the manifolds of a symmetric quasi-periodic orbits around Mercury play a key role as their symmetry properties provide several recovery opportunities to the mission. Consequently, in the future, we envision using the manifolds to get a good idea of what kind of orbits are available at early design stage. This insight will save time by speeding up the design and optimization process and there by saving cost.

Acknowledgements The authors would like to thank Dr. Rüdiger Jehn at the European Space Agency and Prof. Paul Newton at the University of Southern California for their helpful assistance. The first author was supported by the Viterbi School of Engineering Doctoral Fellowship. This work was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.

References

[1] D. Garcia, P. de Pascale, R. Jehn, BepiColombo Cornerstone Consolidated Report on Mission Analysis (ESOC/ESA, Darmstadt, 2007)
[2] R. Jehn R., S. Campagnola, D. Garcia, S. Kemble S., Low Thrust Approach and Gravitational Capture at Mercury, 18th International Symposium on Space Flights Dynamics (Munich, Germany, October 11-15 2004).
[3] S. Campagnola, M.W. Lo, Forbidden Regions and Elliptic halos in the spatial elliptic restricted three-body problem, Proceedings of the 2008 AIAA/AAS Space Flight Mechanics Meeting (to be published)
[4] W.S. Koon, M.W. Lo, J.E. Marsden, S.D. Ross, Heteroclinic Connections Between Periodic Orbits and Resonance Transitions in Celestial Mechanics, Chaos **10**(2), p. 427 - 469 (2000)