WEAK STABILITY BOUNDARY TRANSFERS TO MOON AND MARS

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by

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ABSTRACT

The conventional method to design an interplanetary trajectory is by using patched conic technique in two-body problem. It mainly consists of two impulses namely, trans-planetary injection (ΔV_{TPI}) to send the spacecraft from an Earth Parking Orbit (EPO) into heliocentric trajectory towards the destination planet, and Planetary Orbit Insertion (ΔV_{POI}) to put the spacecraft from a heliocentric trajectory to an orbit around the destination planet. Low-energy transfers are non-conventional methods for interplanetary transfers, and are associated with low-energy with respect to the given major body. Weak Stability Boundary (WSB) transfers, belong to the category of low-energy transfers which take advantage of WSB regions where gravitational attractions of the influencing bodies tend to balance each other, to reduce ΔV_{POI} (to almost zero in case of lunar transfers). The benefits of using WSB transfer over the conventional transfers are less fuel requirement, more flexibility in arrival orbits, extended launch periods and relaxed operational timeline (Parker and Anderson, 2013). WSB transfer has a major disadvantage of long flight duration.

WSB transfer to Moon was first discovered by Belbruno for the Lunar Get-a-Way Special (LGAS) spacecraft which was proposed to use electric propulsion to reach Moon and search for water at its polar regions (Belbruno, 1987). The spacecraft's thrusters were too weak to perform a conventional capture manoeuvre at Moon, so Belbruno proposed an alternative trajectory which would slowly spiral out from Earth, coast to the WSB region so that the spacecraft would be captured into an orbit around Moon. Then it would use its thrusters to spiral down to the final orbit at Moon.

WSB is described by Belbruno and Miller (1993) as "a generalization of Lagrange points and a complicated region surrounding the Moon"; Belbruno (2004) as "a region in phase space supporting a special type of chaotic motion for special choices of elliptic initial conditions with respect to m_2"; Yagasaki (2004) as "a transition region between the gravitational capture and escape from the Moon in the phase space". WSB region is locus of points in the phase space of

restricted three-body problem; these points are functions of energy of infinitesimal body and its position such that its state with respect to the smaller primary transitions between 'capture' (its Keplerian energy with respect to the smaller primary in inertial sense, C3 is negative), and 'escape' (C3 is positive). WSB transfers take advantage of WSB region where the gravitational attraction of influencing bodies tend to balance each other, to reduce the impulse required by the spacecraft on an interplanetary trajectory to establish an orbit around the destination planet/Moon. The invariant manifold structure associated with the Lyapunov orbits near the collinear Lagrange points play an important role in this type of low-energy transfers (Belbruno, 1990; Koon et al., 2007; Anderson and Lo, 2004; Belbruno, 2004; Gomez et al., 2004; Garcia and Gomez, 2007; Topputo et al., 2008; Alessi, 2009 a,b; Fantino et al., 2010).

Belbruno's WSB theory was demonstrated in 1990 when Japanese first Moon mission suffered a failure. This mission consisted of two spacecraft MUSES A and MUSES B. The smaller one, MUSES B was to go to Moon, while the larger one, MUSES A was to remain in Earth orbit as a communication relay. Unfortunately, MUSES B failed and MUSES A did not have sufficient fuel to reach Moon. WSB trajectory was designed for MUSES A which took advantage of gravitational forces of Sun along with Earth and Moon to reach Moon (Belbruno and Miller 1990; Uesugi 1991). In April 1991, MUSES A, renamed as Hiten fired its engines to reach Moon on 2nd October 1991.

Awareness regarding unconventional trajectories in spaceflight was again highlighted by AsiaSat3 in 1998. Due to an upper stage malfunction of Proton rocket, AsiaSat3 was stranded in an elliptical transfer orbit instead of GEO. Although the spacecraft lacked necessary propellant to reach GEO, its controllers were able to perform a series of manoeuvres that sent it around Moon twice and finally to GEO (Ocampo, 2005). The spacecraft was able to operate in limited capacity for several years. Next ESA's SMART-1 (Schoenmaekers et al., 2001) was launched on 27 Sep 2003 reached Moon utilizing a low-energy transfer trajectory like the one designed for LGAS. NASA's Gravity Recovery and Interior Laboratory (GRAIL) Mission in 2011 (Roncoli and Fujii 2010, Chung et al. 2010 and Hatch et al. 2010) was the first mission launched to Moon directly on a low energy transfer. GRAIL launched two spacecraft on board a single launch vehicle and used the long flight duration (~90-114 days) to separate their orbit insertion epochs by 25 hours. Low energy transfer is proposed for missions like Multi Moon Orbiter (Ross et al., 2003; Ross et al., 2004), Europa Orbiter (Sweetser et al., 1997; Johannesen and D'Amario, 1999; Heaton et al., 2002) and BepiColombo (Jehn et al., 2004; Campagnola and Lo, 2007; Jehn et al., 2008).

Using the dynamical system theory some natural phenomena like resonance hopping and capture observed in Jupiter comets has been explained (Belbruno and Marsden, 1997; Lo and Ross, 1997; Howell et al., 2000; Koon et al., 2007). Further, Belbruno and Gott (2005) attempt to explain the BigSplat hypothesis and Belbruno et al. (2008) explain the lithopanspermia hypothesis using the dynamical system theory.

The work carried out in this thesis mainly concerns with the design of WSB transfers to Moon and Mars and studies their dynamics. In order to study the dynamics of WSB trajectories to Moon, lunar capture trajectories and geocentric elliptical orbits are represented on phase space diagrams. These results will be useful for mission designers as the phase space diagrams with colour code on time of flight (and capture) enables the selection of departure (and arrival) orbits and total time of flight can be approximated without actually constructing the complete trajectory. It is known that the positional phase angle of perilune of lunar capture trajectories lies within -55^0 to 55^0 and 125^0 to 235^0 (Yamakawa, 1992). With the help of numerical simulations it is found that this holds good for lower altitudes but it is violated to some extent for higher apolune altitudes.

Dynamics of capture orbits at Mars are studied in the framework of restricted three-body problem. It is found that for higher periapsis altitudes (≥10,000 km) almost all ranges positional phase angle of periapsis in Sun-Mars fixed rotating frame yields capture orbits. Hence in order to obtain WSB trajectories to Mars, the algorithm has to be targeted to high periapsis altitudes to increase the possibility of finding capture orbits.

Numerical algorithms are developed to obtain WSB trajectories to Moon and Mars in real world scenario. These algorithms start from an EPO, use forward propagation to reach a capture trajectory at Moon/Mars. Literature is flooded with back-propagation algorithms to find WSB trajectories, which face major problem of launch vehicle constraint satisfaction. Back-propagated trajectories may lead to a patching point, too expensive for a launch vehicle to satisfy its maximum payload constraints (mainly AOP and inclination). This drawback is eliminated in this case and these algorithms can be applied to both circular and elliptical EPO. Also given a departure date and EPO conditions, a number of WSB arrival orbits can be found using the given algorithm with marginal difference in impulse requirements but varying arrival orbits. In case of conventional transfers, the inclination of arrival orbit depends on declination of incoming hyperbola. But for WSB transfers different inclination arrival orbits are obtained for the same incoming trajectory. The one suiting our requirements can be selected. Another advantage of this algorithm is that the WSB trajectories are developed in high fidelity force model which can be used for actual missions.