Lunar Navigation with Libration Point Orbiters and GPS

J. Russell Carpenter*

NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

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NASA is currently studying a Vision for Space Exploration[1] based on spiral development of robotic and piloted missions to the moon and Mars, but research into how to perform such missions has continued ever since the first era of lunar exploration. One area of study that a number of researchers have pursued is libration point navigation and communication relay concepts. These concepts would appear to support many of NASA's current requirements for navigation and communications coverage for human and robotic spacecraft operating in cis-lunar space and beyond. In trading libration point concepts against other options, designers must consider issues such as the number of spacecraft required to provide coverage, insertion and stationkeeping costs, power and data rate requirements, frequency allocations, and many others.

The libration points, which Figure 1 depicts along with a typical cis-lunar trajectory, are equilibrium locations for an infinitesimal mass in the rotating coordinate system that follows the motion of two massive bodies in circular orbits with respect to their common barycenter. There are three co-linear points along the line connecting the massive bodies: between the bodies, beyond the secondary body, and beyond the primary body. The relative distances of these points along the line connecting the bodies depend on the mass ratios. There are also two points that form equilateral triangles with the massive bodies. Ideally, motion in the neighborhood of the co-linear points is unstable, while motion near the equilibrium points is stable. However, in the real world, the motions are highly perturbed so that a satellite will require stationkeeping maneuvers.

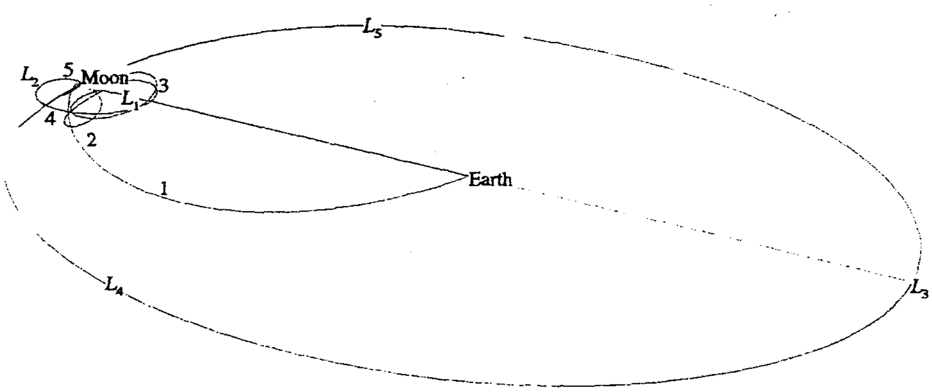

Figure 1: **Representative cis-lunar trajectory: 1) cis-lunar transfer, 2) lunar swingby, 3) L_1 orbit, 4) L_1 departure, 5) capture into lunar polar orbit and descent.**

A libration point concept advocated for many years by Farquhar[2] is a lunar relay satellite operating in the vicinity of the translunar Earth-Moon libration point, often designated L_2, providing "Earth-to-lunar far-side and long-range surface-to-surface navigation and communications capability." Reference [2] lists several advantages of such a system in comparison to a lunar orbiting relay satellite constellation. Among these are one or two vs. many satellites for coverage, simplified acquisition and tracking due to very low relative motion, much longer contact times, and simpler antenna pointing; however, access from lunar polar

*Aerospace Engineer, Flight Dynamics Analysis Branch, Code 595, ION Member.

sites is challenging. An obvious additional advantage of such a system is that uninterrupted links to Earth avoid performing critical maneuvers "in the blind," when direct communications to Earth is not possible. Renault and Scheeres[3] have estimated that the stationkeeping cost for such a satellite, when considering the impact of navigation errors of 10 km and 10 mm/sec, would be on the order of 2–3 m/sec per month, assuming maneuvers approximately every two days. A survey of stationkeeping costs for a larger variety of libration point orbits in the Earth-Moon system has been performed by Folta and Vaughn[4].

Another concept Farquhar described is the use of the cis-lunar Earth-Moon libration point (L_1) for lunar orbit rendezvous, rather than low lunar orbit as was done for Apollo. Farquhar claims this technique requires only slightly higher fuel cost than low lunar orbit rendezvous for short-stay equatorial landings. More recently, Condon and Wilson[5] have estimated that libration point rendezvous missions have significant advantages over lunar orbit rendezvous missions when global access, long stay times, and anytime aborts are driving requirements for human exploration missions. However, these trades, and the trade vs. lunar surface rendezvous, are significantly complicated by as yet undetermined abort requirements.

Farquhar also described an interplanetary transportation system that would use libration points as terminals for an interplanetary shuttle. This approach would offer increased operational flexibility in terms of launch windows, rendezvous, aborts, etc. in comparison to elliptical orbit transfers. More recently, other works[6, 7] have shown that patching together unstable trajectories departing Earth-Moon libration points with stable trajectories approaching planetary libration points may also offer lower overall fuel costs than elliptical orbit transfers. The lunar navigation infrastructure should evolve to support such concepts.

Another concept Farqhuar described was a deep space relay at an equilateral Earth-Moon libration point (L_4 and/or L_5) that would serve as a high data rate optical navigation and communications relay satellite. The advantages in comparison to a geosynchronous relay are minimal Earth occultation, distance from large noise sources on Earth, easier pointing due to smaller relative velocity, and a large baseline for interferometry if both L_4 and L_5 are used. Such a relay could initially support lunar missions as well.

Barton et al.[8] studied the use of the Global Positioning System (GPS) for navigation enroute between the earth and the moon. Assuming modest modifications that would improve GPS receiver sensitivity by approximately 10 dB and a high-gain directional receiver antenna, they showed that GPS signals viewed over the earth's limb would support post-translunar injection (TLI) navigation out to about half the lunar distance. They also showed GPS navigation could support a mid-course trim burn for at least several hours after TLI, but if the trim burn was more than 8 hours after TLI, there was not enough GPS information to estimate the post-burn state. This level of GPS coverage might support the L_1 lunar rendezvous scenario, especially if augmented by additional signals from NASA's Tracking and Data Relay Satellite System (TDRSS), or from navigation assets in the vicinity of the moon. More significant improvements in GPS receiver sensitivity could likely be achieved by using new, dataless GPS signals and telemetering the GPS navigation message via a distinct communications link to lunar navigation receivers, avoiding the need for the users to decode the GPS ephemerides. Such a system might support limited GPS navigation all the way to the Earth-side lunar surface.

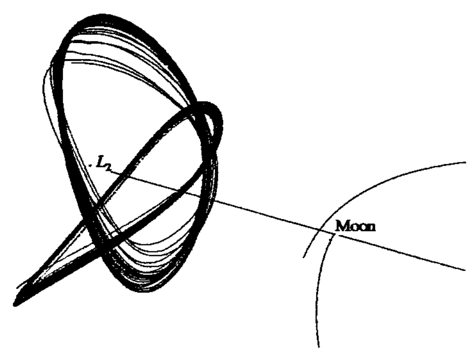

Figure 2: Earth-Moon L_2 Orbiters' trajectories. The direction of the moon's motion is toward the viewer, and the earth is to the right of the scene. The amplitudes of the orbits in the direction normal to the moon's orbit plane are approximately 25,000 km, and they extend approximately 50,000 km on either side of the Earth-Moon-L_2 line. The amplitude of the motion toward and away from the moon covers about 25,000 km. These orbits are nearly as large as would be feasible, and may provide adequate coverage of the lunar polar regions.

NASA Goddard has made a preliminary assessment of a lunar navigation infrastructure based on the concepts described by Farquhar and Barton et al. Our study[9] indicates that accuracies of better than 1 km and 5 cm/sec may be feasible for a cis-lunar transfer scenario that uses GPS pseudoranges in combination with one-way Doppler measurements from one or more Earth–Moon L_2 Orbiters that Figure 2 shows. These are quite promising in comparison with the trans-lunar post-maneuver results on the order of kilometers and dozens of centimeters per second that Beckman and Concha[10] achieved during Lunar Prospector using two-way Doppler from Deep Space Network 34- and 26-meter tracking sites. It should be noted that the real-world results of Reference [10] were achieved in the face of all the constraints posed by an operational environment, including, most notably, imperfectly performed maneuvers that this study did not address. Nevertheless, these results would appear to support the need for further investigation of the Earth–Moon L_2 Orbiter concept as a means to provide a great deal of capability with minimal investment, as a starting point for a comprehensive lunar and planetary navigation and communications infrastructure beyond near Earth orbit.

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