Lunar Sample Return via the Interplanetary Superhighway

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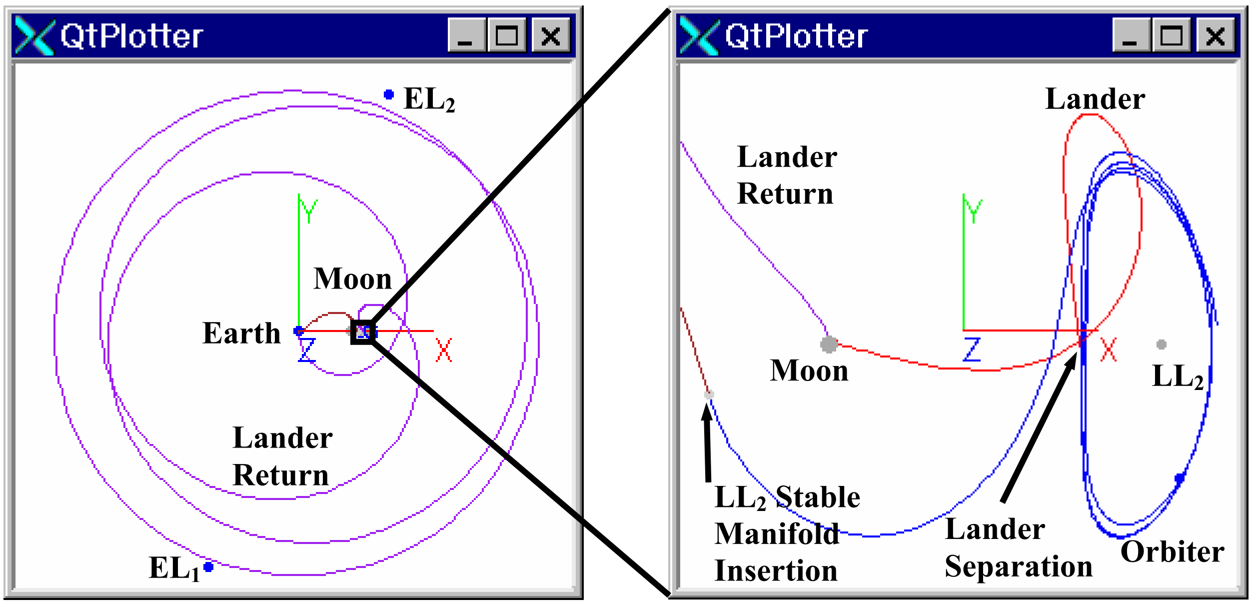

Figure 1. The entire Lunar Sample Return mission trajectory is shown in the Earth-Moon rotating frame. The Earth launch is in brown, the insertion into LL_2 is in blue, the lander orbit to the Moon in red, and the lander return orbit is purple. The expanded detailed plot on the right shows the halo orbit about LL_2 and the landing . The dynamics of the lander return trajectory (purple) is not apparent in this figure, but is revealed in Figure 6 under the Sun-Earth rotating frame.

ABSTRACT

The Aitken Basin at the lunar south pole is the largest impact crater known in the Solar System, piercing the Moon's mantle. A National Research Council panel recently recommended that NASA consider a robotic Lunar Sample Return mission to collect samples from the Aitken Basin and return them to Earth for study [1]. This paper describes several approaches to a Lunar Sample Return mission. The Lunar Sample mission consists of two spacecraft: a communications orbiter module and a lander/sample return module; the combined flight system is carried to the Moon. The desired landing site in this case is on the backside of Moon which cannot be seen from Earth; this is why a communications orbiter module is needed. Knowledge of the Interplanetary Superhighway tunnels and their dynamics provided good initial guess solutions for the final integrated solutions (see Figure 1). The exploration of the design trade space was facilitated by JPL's LTool2001 mission design tool.

1. INTRODUCTION

It has been decades since the last of the Moon rocks were gathered by astronauts and returned to Earth by the Apollo Program. There is now renewed interest in returning to the Moon. Where humans are involved, the roundtrip flight time must be minimized. However, in the case of a robotic sample return mission, the flight time is not as critical. It may be relaxed and lengthened to minimize the energy required to return samples from the Moon.

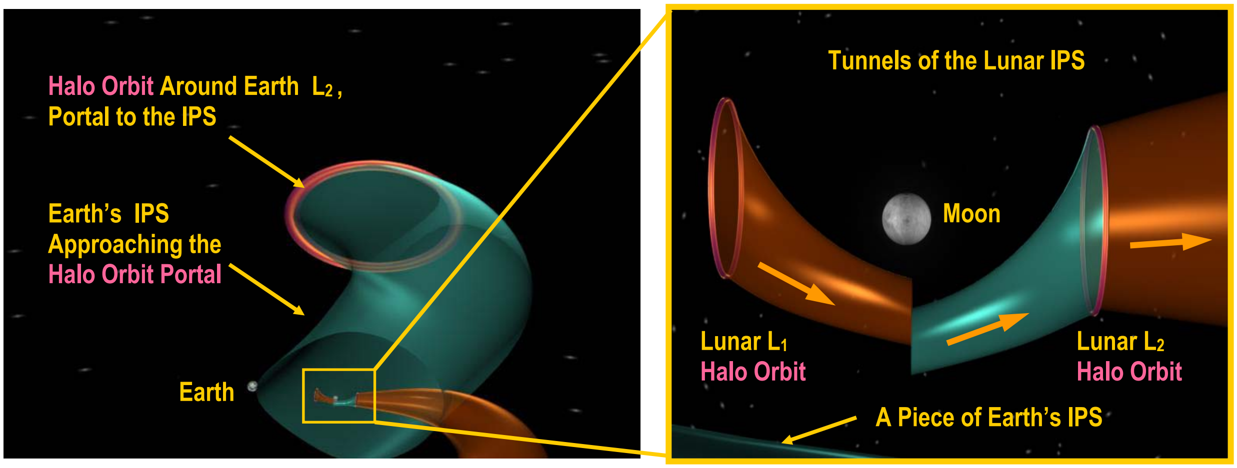

Figure 2. Artist's conception of portions of the Interplanetary Superhighway (IPS, tubes) of the Sun-Earth-Moon System generated by the halo orbits (large periodic orbits around the unstable Lagrange Points L_1, L_2, and L_3). Orbits on the blue-green tubes approach the halo orbits, while those on the red tubes go away from the halo orbits. Thus, the halo orbits are the portals, the literal "Highway Interchanges" to the Interplanetary Superhighway. The exploded view on the right is the Lunar portion of the Interplanetary Superhighway. Arrows indicate the direction of transport.

In particular, we can take our cue from comets and asteroids and exploit the low energy natural dynamics of the Interplanetary Superhighway (IPS) in the Earth's Neighborhood as shown in Figure 2. The Earth's Neighborhood is the spherical region of space around the Earth with a radius of roughly 2 million km.

2. THE IPS IN THE EARTH-MOON ENVIRONMENT

The Interplanetary Superhighway is a network of tunnels and passageways that connects various regions within the Solar System. (see Lo and Ross [2], Lo [3] for more details). It is generated by the invariant manifolds of the unstable periodic and quasiperiodic orbits within the entire Solar System modeled as a series of coupled circular restricted three body systems. In the Earth's Neighborhood, this complex web of passageways provide many interesting low-energy trajectories we used to design a Lunar Sample Return mission using libration orbits about LL_1 (Lunar L_1), LL_2, EL_1 (Earth L_1), and EL_2 as shown in Figure 3 below.

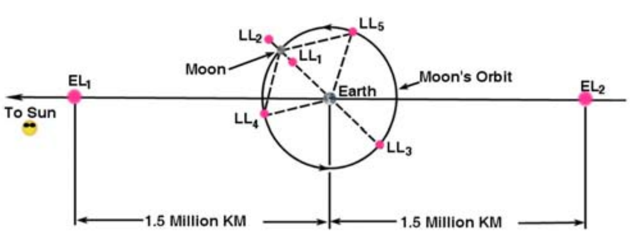

Figure 3. The Lagrange Points of the Moon (LL_1…LL_5) and the Earth (EL_1, EL_2) in Earth's Neighborhood in Earth rotating coordinates. The horizontal-axis containing the Sun and the Earth. Adapted from Figure 7. of Farquhar [4].

The idea of using lunar libration orbits for space missions has a long history. Colombo [5] was the first to consider it. In 1966 Farquhar [6] proposed a "halo orbit" around LL_2 for a single communications satellite to link the Earth with the farside of the Moon (see Farquhar [4] for a more complete history). After nearly 40 years, this idea has surfaced again for the Lunar Sample Return mission.

MISSION DESCRIPTION

The Lunar Sample Return mission consists of two spacecraft: a communications orbiter module (Orbiter) and a lander/sample return module (Lander). The two modules are combined into a single flight system (Combo) to reach the Moon where the two modules are then separated. Several different scenarios are studied and described below. The landing site in all cases is at 180 deg. longitude, -57 deg. Latitude in the Aitken Basin, the largest known crater in the Solar System. This is on the backside of Moon so a separate spacecraft module is required for communications with Earth. We exploit the heteroclinic dynamics that connect the LL_1, LL_2, EL_1, and EL_2 regions to provide flexibility in various design options used. This is the same dynamics used to design the Earth return trajectory of the Genesis mission which just launched in August 8, 2002 (see Lo et al. [7], and Howell, Barden, Wilson, Lo [8]). Knowledge of the Interplanetary

Superhighway tunnels and their dynamics provides a quick modular approach to designing libration missions. It also supplies good initial guess solutions for obtaining the more accurate integrated solutions. The exploration of the design trade space was facilitated by JPL's LTool2001 mission design tool.

MISSION DESIGN WITH IPS SEGMENTS

In this paper, we describe several scenarios for a Lunar Sample Return mission using the tubes of the Interplanetary Superhighway in the Earth's Neighborhood provided by dynamical systems theory. An excellent exposition of the application of dynamical systems theory for halo orbit misisons is given by Gomez et al. [8]. The trajectory segments within the Interplanetary Superhighway in the Earth's Neighborhood provide some of the lowest energy pathways within the Earth-Moon system. Thus, libration orbits play a much greater role than as venues for solar and astrophysical space observatories. They are the generators of and the portals to this vast system of low energy trajectories.

One of the key setbacks for mission design in the libration regime has been the loss of orbital elements. Since libration orbits are nonlinear trajectories in the three body problem, the Jacobi constant is the only "integral" available and then only in the Restricted Three Body Problem formulation. This means one is unable to characterize libration orbits by parameters such as semimajor axis, eccentricity, inclination, etc. as one can for conic orbits, since orbital elements are "integral" quantities in the two body problem. In its place, the knowledge of the location of libration orbits in space and their associated invariant manifold tubes provide "replacement structures" for handling mission design with libration orbits.

Our knowledge of the libration orbit design space has advanced to the point where some rudimentary standard orbital segments may be easily constructed and used in 'tinker-toy' fashion to provide a modular approach to designing such missions. Some of these standard components are halo and Lissajous orbits around L_1 and L_2, orbits connecting halo and Lissajous orbits between L_1 and L_2, tubes leaving the planet to approach the halo orbit, tubes leaving the halo orbit to approach the planet, tubes leaving the halo orbit to escape the planet, tubes from one of the planet intersecting the tubes of another planet or satellite (see [10] and [11] for examples). These basic components can be combined with traditional planetary flybys and low thrust segments to further expand the mission design space. For the basic 'libration components' listed above, estimates of time and energy requirements are available in some instances (such as in the case of the Earth's Neighborhood) to provide quick back of the envelope estimates such as was possible with conic orbits. Thus, a mission designer can quickly string these libration components together to provide a preliminary mission design. This design can then be validated using tools like LTool where the components may be integrated using a more accurate model of the Solar System.

This approach allows the designer to select the orbital components in the mission design prior to the trajectory optimization process. As we understand more about the design process above, with the help of additional theoretical understanding and empirical data on the Interplanetary Superhighway, automation and faster algorithms may be achieved through this approach.

3. MISSION SCENARIOS

The following describes three different mission scenarios using libration point orbits: transfer via LL_2, LL_1, and EL_1. A conic sample return mission to the moon is also considered for comparison. We will refer to these scenarios as the LL_2 Case, the LL_1 Case, the EL_1 Case, and the Conic Case in this paper.

THE LL_2 CASE: GOING DIRECTLY TO LL_2

In the LL_2 Case, the combo (combined flight system) is transferred to an LL_2 Lissajous orbit directly via a heteroclinic connection on the stable manifold of the LL_2 Lissajous orbit. The lander is separated from the orbiter at the separation point. The sample is returned to earth via EL_2 to reduce the ΔV required. The performance is summarized in Table 1. In this case, all trajectory segments have been differentially corrected to produce an integrated end-to-end trajectory.

LL_2 Case Mission Sequence	Date (2009)	Flight Time (days)	Combo ΔV (m/s)	Lander ΔV (m/s)	Orbiter ΔV (m/s)
Translunar Injection	6/14	0	3122		
Manifold Insertion	6/18	4	570		
LL_2 Halo Arrival	6/25	11			
Lander LL_2 Departure	7/7	23		35	
Lander Landing	7/17	33		2335	
Lander Liftoff	7/28	44		2424	
Earth Return	11/7	146			
Determin. ΔV Total			3692	4794	0
Nav. ΔV Estimate			25	50	25
TOTAL			3717	4844	25

Table 1. Case LL_2 performance. Direct transfer to LL_2 Lissajous orbit with sample return via EL_2. ΔV values from fully integrated trajectories.

The trans-lunar injection is assumed to be from a Shuttle-like (200-km altitude, 28.5-degree inclination, circular) orbit. The Combo is injected on June 14, 2009 with 3122 m/s. See Figure 4 for the trans-lunar orbit; for the rest of the discussion in this paragraph, see Figure 1. The combo is inserted into a heteroclinc connection from LL_1 to LL_2 (a trajectory on the stable manifold of the LL_2 Lissajous orbit) on June 18, 2009 with 570 m/s. This ΔV places the combo in an LL_2 Lissajous orbit on June 25, 2009. The lander is separated from the communications orbiter on July 7, 2009, with 35 m/s at the closest point from the moon when it crosses the XZ-plane. See Figure 1 for the lander separation point. The lander lands on the far side of the moon (180 deg. longitude and –57 deg. latitude) on July 17, 2009, with a deceleration of 2335 m/s. See Figure 1 for the lander orbit. After the sample collection, it lifts off from the moon in the direction of EL_2 on July 28, 2009 with 2424 m/s. See Figure 5

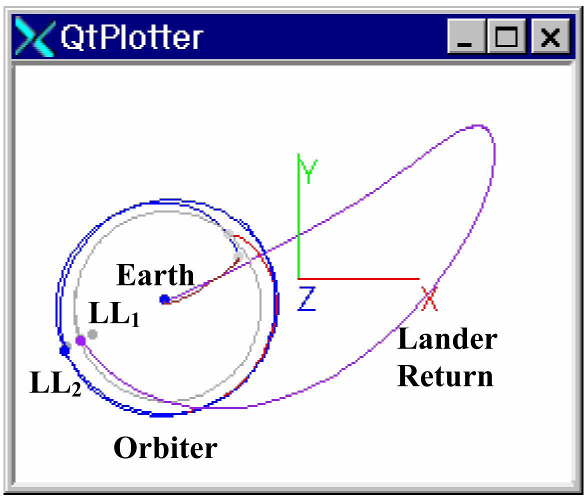

Figure 5. The entire trajectory is displayed in an inertial frame, centered at earth. The trans-lunar leg is in brown, the LL_2 Lissajous in blue, the lander insertion in red, and the lander return in purple. The moon's orbit is in gray. LL_1 and LL_2 are snapshots at the time of the lander return lift-off; they move counterclockwise with respect to earth. Note that the LL_2 Lissajous orbit in blue appears as an elliptical orbit in this frame. Also note that the lander return leg in purple is not a conic orbit with respect to the earth.

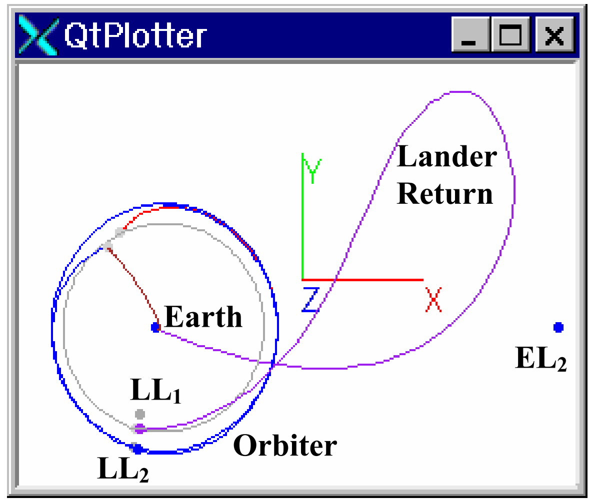

Figure 6. The entire trajectoriy is displayed in Sun-Earth rotating frame, centered at earth. The color scheme follows the convention established. In this frame the LL_2 Lissajous orbit in blue is not apparent. However, the dynamics of the lander return trajectory is revealed; it comes close to making a Lissajous orbit around EL_2. LL_1 and LL_2 move counterclockwise about the earth.

(inertial frame), Figure 1 (Earth-Moon rotating frame), and Figure 6 (Sun-Earth rotating frame) for the complete lander return trajectory in different frames. Note that the dynamics of the return trajectory is most apparent in the Sun-Earth rotating frame as in Figure 6. It returns to the earth on November 7, 2009. The communications orbiter continues its Lissajous orbit around LL_2 until end of operations.

The LL_1 Case

In the LL_1 Case, the combo is injected into a stable manifold trajectory of the LL_1 Lissajous orbit. Then,

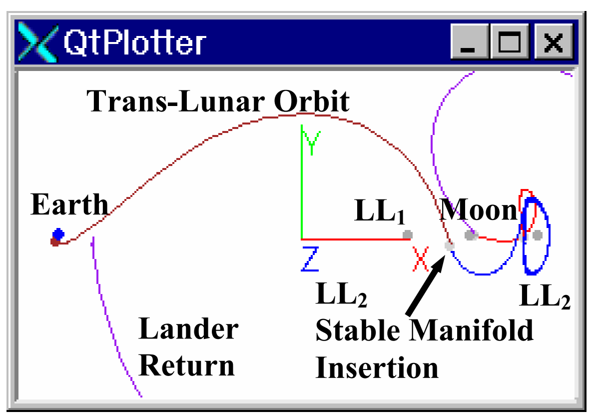

Figure 4. The trans-lunar orbit in the Earth-Moon rotating frame is shown in brown. The plot is centered at LL_2 to make the Lissajous orbit appear nicely. In this plot, the Earth will move along the X-axis due to the eccentricity of the lunar orbit.

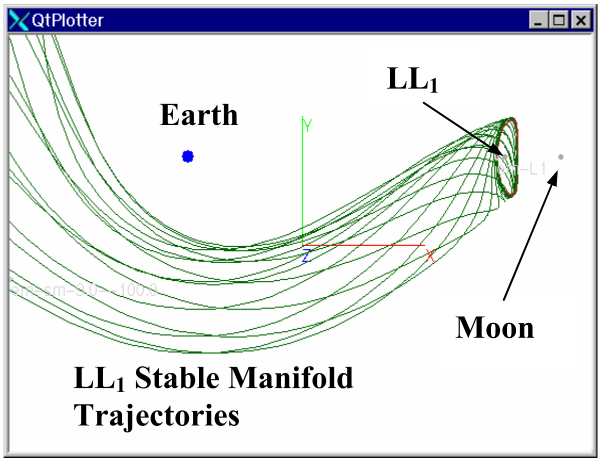

Figure 7. LL_1 stable manifold trajectories in dark green are displayed in the Earth-Moon rotating frame, centered at LL_1. The LL_1 Lissajous orbit is in brown.

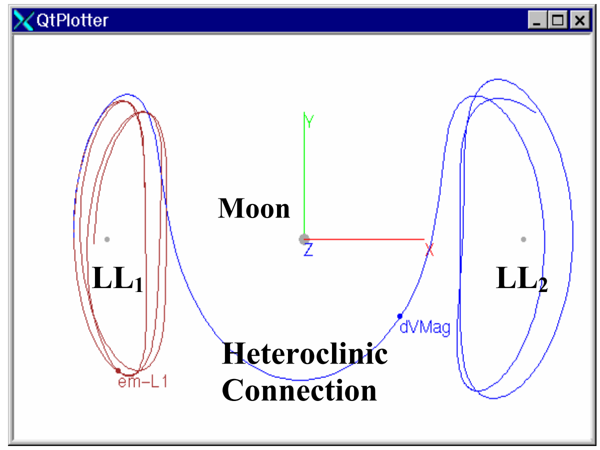

Figure 8. A heteroclinic connction on the stable manifold of the LL_2 Lissajousorbit is generated from LL_1 Lissajous to LL_2 in the Earth-Moon rotating frame, centered at the moon. The Lissajous orbits appear a bit scattered due to the eccentricity of the Moon's orbit.

the orbiter is transferred to an LL_2 Lissajous orbit via a heteroclinic connection. The lander is sent to the landing site on the moon directly from the LL_1 Lissajous orbit. See Figure 7 for various trajectories on the LL_1 stable manifold. The trajectories in this case have not been differentially corrected. Thus, the ΔV's and dates represented in Table 2 are estimates. The estimated trans-lunar injection is 3100 m/s on June 9, 2009. The combo is inserted onto the stable manifold on June 14, 2009 with approximately 600 m/s. This ΔV inserts the combo into an LL_1 Lissajous orbit. First, the communications orbiter is separated from the lander to an LL_2 Lissajous orbit. A small ΔV on the order of 10 m/s at the XZ-plane crossing point closest to the earth places the spacecraft in the LL_2 Lissajous orbit via a heteroclinic connection. Figure 8 shows a heteroclinic connection orbit. One rev after the communications orbiter separation, the lander is sent on its way to the moon approximately on July 10, 2009. An estimated 95 m/s places the lander on the moon. The touch down deceleration is approximately 2330 m/s. The rest of the mission scenario is similar to the LL_2 Case; it is represented by the shaded sequences in the Table 2.

LL_1 Case Mission Sequence	Date (2009)	Flight Time (days)	Combo ΔV (m/s)	Lander ΔV (m/s)	Orbiter ΔV (m/s)
Translunar Injection	6/9	0	3100		
LL_1 Halo Insertion	6/14	5	600		
Orbiter Departs LL_1	6/19	10			14
Orbiter LL_2 Arrival	7/7	28			0
Lander Departs LL_1	7/10	31		95	
Lander Landing	7/16	37		2330	
Lander Liftoff	7/28	49		2424	
Earth Return	11/7	151			
Determin. ΔV Total			3700	4849	14
Nav ΔV Estimate			25	50	25
TOTAL			3725	4899	39

Table 2. Case LL_1 performance. The combo sent to LL_1 Lissajous orbit. The ΔV values are estimated.

EL_1 CASE

In order to lower the cost of ΔV to reach the LL_2 Lissajous orbit, an EL_1 Lissajous orbit may be used.

EL_1 Case Mission Sequence	Date (2009)	Flight Time (days)	Combo ΔV (m/s)	Lander ΔV (m/s)	Orbiter ΔV (m/s)
Earth Launch	5/30/8	0	3193		
EL_1 Insertion	8/29/8	91	60		
LL_2 Halo Arrival	6/15	391	13		
Lander Departs LL_2	7/7	403		35	
Lander Landing	7/17	413		2335	
Lander Liftoff	7/28	424		2424	
Earth Return	11/7	553			
Determin. ΔV Total			3266	4794	0
Nav ΔV Estimate			25	50	25
TOTAL			3291	4844	25

Table 3. Case EL_1 performance. The combo is sent to LL_2 via EL_1. The ΔV values are estimated.

The resulting orbit is quite similar to the Genesis orbit in its starting phase. Mission sequences and the estimated ΔV's are tabulated in the Table 3. The combo is sent to an EL_1 Lissajous orbit from the Earth parking orbit using 3193 m/s. The EL_1 Lissajous insertion is 60 m/s. The duration between the launch and the EL_1 insertion is approximately 91 days. The EL_1 Lissajous orbit insertion nearly automatically leads the spacecraft to the LL_2 Lissajous orbit in approximately 300 days later. The insertion into LL_2 Lissajous orbit is approximately 13 m/s. The rest of the mission scenario is exactly the same as in the LL_2 Case; it is represented by the shaded sequences in the Table 3.

CONIC CASE

The Conic Case (Williams [12]) assumes the trajectory for the mission consists of conic arcs which are patched together. No further refinement was performed. This provides a fast estimate of the mission performance and a comparison with the low-energy missions. The mission sequence and ΔV's are summarized in the Table 4.

Conic Case Mission Sequence	Date (2009)	Flight Time (days)	Combo ΔV (m/s)	Lander ΔV (m/s)	Orbiter ΔV (m/s)
Translunar Injection	7/16	0	3100		
Separation	7/17	1			
Lunar Orbit Insertion	7/20	4.5		979	481
Lander Apoapsis Burn	7/20	4.54		23	
Lander Landing	7/20	4.58		1703	
Lander Liftoff	8/3	18.5		3220	
Earth Return	8/8	23			
Determin. ΔV Total			3100	5925	481
Nav ΔV Estimate			25	50	25
TOTAL			3125	5975	506

Table 4. Conic Case performance. The orbiter is set in a highly elliptical orbit. The ΔV values are estimated.

The combo is sent to an orbit around the moon on July 16, 2009, with 3100 m/s. One day later the lander and the orbiter are separated. The communications orbiter goes on a highly elliptical orbit (100 km x 8700 km, 12 hr period) with periapse facing the far side of the moon on July 20, 2009, using 481 m/s. The lander is inserted into a 100-km circular orbit on July 20, 2009, using 979 m/s. The lander is then sent to lunar surface using 23 m/s. The lander deceleration is 1703 m/s. After collecting samples, the lander/return module lifts off on August 3, 2009, with approximately 3220 m/s for a direct return to earth on August 8, 2009.

MISSION PERFORMANCE

The mission performance for each of the cases considered above is summarized and compared in Table 5. The ΔV performance of the combo, lander, communications orbiter, and their combined sum are listed individually for each case. The Total Time is the total elapsed time for the mission

Note that, since the LL_2 Lissajous orbit is always facing the far side of the moon, the lander is always in view of the communications orbiter for all libration orbits we considered. This is an advantage over the conic trajectory around the moon. The ΔV savings is not as apparent for sending the spacecraft via either LL_1 or LL_2 Lissajous orbit in comparison to the conic estimate; however, there is a considerable ΔV saving of more than 400 m/s in sending the combined spacecraft via EL_1 than via either LL_1 or LL_2. There is also a considerable ΔV savings by returning to earth via EL_2 rather than a direct return. The ΔV for returning via EL_2 is 2424 m/s. The Soviet's Lunar series used approximately 2.7 km/s to return to earth directly from the near side of the moon (Sweetser [13]). There is a saving of 276 m/s. Besides, it is not apparent whether there can be a direct transfer trajectory with only a single lift from the far side of the moon to earth. The conservative estimate of 3220 m/s was obtained by adding the moon's hyperbolic escape velocity and the conic return trajectory to earth (Williams, [12]).

Case	Combo ΔV (m/s)	Lander ΔV (m/s)	Orbiter ΔV (m/s)	Total ΔV (m/s)	Total Time (days)
LL_2	3717	4844	25	8586	146
LL_1	3725	4874	39	8638	151
EL_1	3266	4844	25	8135	553
Conic	3100	5925	481	9506	23

Table 5. This table summarizes performance of the combo, the lander, and the communications orbiter. The Conic Case and the EL_2 Case are added for comparison.

4. CONCLUSIONS

We described three scenarios for a Lunar Sample Return mission using the tubes of the Interplanetary Superhighway in the Earth's Neighborhood provided by dynamical systems theory. The trajectory segments within the Interplanetary Superhighway in the Earth's Neighborhood provide some of the lowest energy pathways within the Earth-Moon system. The

Interplanetary Superhighway provided a modular approach to mission design in libration space. The resulting missions require less propulsion than a mission using standard conic arcs only for its trajectory design. In general, however, the use of the low-energy Interplanetary Superhighway requires longer travel time than conventional high-energy hyperbolic transfers. The LTool2001 was able to provide a fully integrated trajectory whereas, within the same time frame, the standard conic-based trajectory tools could not respond as quickly.

The Interplanetary Superhighway requires development, just as any other natural resource must be developed in order to be fully utilized. One of the key areas for further study is the role of continuous thrust in this regime. Preliminary work has demonstrated that there is a close connection between low-thrust trajectories and those within the Interplanetary Superhighway. The most obvious examples are cometary orbits which are 'continuous-thrust' objects in space that follow the Interplanetary Superhighway (see Howell, Marchard, and Lo [14]). Another area where development is needed is to understand the relation between the libration regime and the conic regimes, particularly hyperbolic flybys. Finally, the Interplanetary Superhighway itself needs to be mapped, and additional tools need to be developed to explore its structure in order to provide new algorithms and orbits for mission design in this rich regime.

ACKNOWLEDGEMENTS

This work was carried out at the Jet Propulsion Laboratory of the California Institute of Technology under a contract with the National Aeronautics and Space Administration. The work was supported by the Decade Planning Team, the JPL Team X, the NASA EXploration Team. Special thanks to Steven Williams of JPL for providing the data for the Lunar Sample Return Mission using conic orbits. Thanks to Theodore Sweetzer of JPL for helpful conversations. Thanks also to Cici Koenig of the Caltech Graphics Group for providing some of the graphics. Thanks to Stacy Weinstein for a thorough review and helpful comments. Many thanks to the JPL LTool Team for their support: Brian Barden, James Evans, George Hockney, and Larry Romans; and former team members: Julia Bell, Larry Bright, David Glicksberg, Richard Pomphrey, John Schwartz, and Roby Wilson.

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