ANALYSIS INTO THE FUEL EFFICIENCY AND TIME CONSIDERATIONS OF DIFFERENT MANOEUVRES IN GETTING LUNAR MISSION ONE TO THE MOON

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Introduction

This report is going to make a few assumptions about Lunar Mission One (LM1) based on information provided by the LM1 website. LM1 is currently still in its early stages of development, so many of the details will be subject to change. Information about LM1 can be found at https://lunarmissionone.com/.

An important aspect of any space mission is to be able to use all resources and technology available as efficiently as possible to substantially minimise the cost in launching, operating, and transporting the spacecraft to the intended destination. For Lunar Mission One, the importance of this factor is more significant as they do not have access to funding comparable to well-established government Space Agencies such as National Aeronautics and Space Administration (NASA) or the European Space Agency (ESA). The result of this is the need to effectively reduce the cost of all stages of the mission, and specifically discussed in this paper, the fuel used in getting the lander from Earth to the Surface of the Moon.

In addition to the Low Earth Orbit (LEO) and intended lunar polar orbit, this paper will focus on potential methods for trans-lunar injection, starting with the direct transfer and followed by low-energy ballistic transfers. With each of these taking the spacecraft on completely different trajectories in order to reach the Moon, considerations for mission duration will also be made.

Prior to research on this topic I was aware of the classical methods of reaching the Moon based on NASA’s Apollo mission, but was not aware of the detail in each stage, such as how they are mapped out. A majority of my research took place on Google Scholar where I found most of the appropriate journals and other websites containing the relevant information. Despite this, there was very little to no useful material on certain aspects of this topic, but with access to more journals and articles, there are many fields that could be enhanced.

Abstract

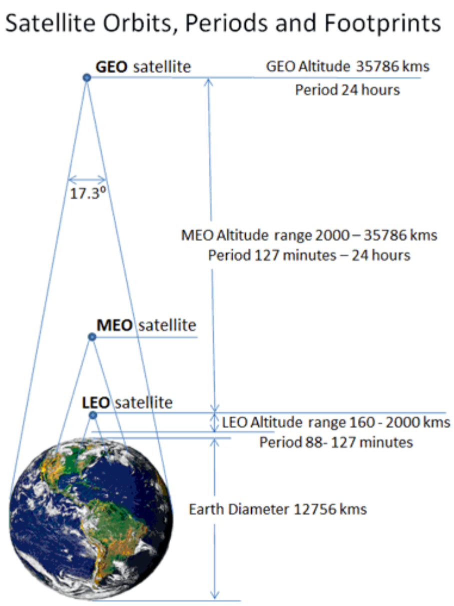
This paper investigated the likely flightpath and fuel efficiency of different potential routes that Lunar Mission One could take to the moon, and the effect that each of these routes would have on overall duration. Research was made into the trajectories of previous spacecraft that made their way to the Moon as well as methods that had not been achieved but were theoretically sound. I predicted that the most fuel efficient way of reaching the Moon would be to use the more unconventional 'lunar swing-by' to bring the craft into a highly elliptical orbit and back down to the Moon with the minimal ΔV required. Consequently, I determined that this would likely mean the conventional Hohmann transfer would be an inefficient method of trans-lunar injection which will be discussed later. Research showed that despite its effectiveness, the Hohmann transfer was particularly inefficient on fuel use, and alternate methods using ballistic transfers would help to get Lunar Mission One to the Moon using less fuel, however taking significantly more time to do so.

This paper therefore concluded that despite the shortcomings of the Hohmann transfer, it was deemed more reliable and effective to achieve the most direct route to the moon.

Methodology

Getting into Low Earth Orbit (LEO)

Launching a spacecraft from the surface of the Earth and achieving a stable and circular orbit is the most fuel consuming part of any Mission. This is partly due to the fact the spacecraft must accelerate to over 7.5kms^{-1} from a relatively slow velocity. The craft can utilise Earth's rotation to minimise Delta-V (a change in velocity) to reach orbit. LM1 will have to achieve an orbit around the Earth in the same direction as the Moon's rotation for the sake of mission simplicity and minimising fuel consumption.



Orbital Altitude Diagram
(Electropedia, 2015)

The weight of the spacecraft is also of great significance at the beginning of the mission as it contains more stages and more fuel than at any other time, and whilst the ascent is taking place, a lot more fuel is used to counteract the vertical acceleration due to gravity. As NASA claims, ‘Travelling from the surface of Earth to Earth orbit is one of the most energy intensive steps of going anywhere else’ (Pettit, 2012). This heavy use of propellant will play a large role in the fuel consumption of the mission but is practically unavoidable due to there being no significantly better method of achieving LEO.

There are a number of potential ways to get into space, for example the SKYLON spaceplane which is ‘an unpiloted, reusable spaceplane intended to provide reliable, responsive and cost effective access to space’ (European Space Agency, 2011). Using the incredibly efficient SABRE (Synergetic Air-Breathing Rocket Engines), this aircraft can efficiently burn fuel with oxygen from the atmosphere until it reaches a specified altitude which causes the engines to automatically switch into rocket mode, using its own oxidiser instead, eventually reaching space and achieving its mission.

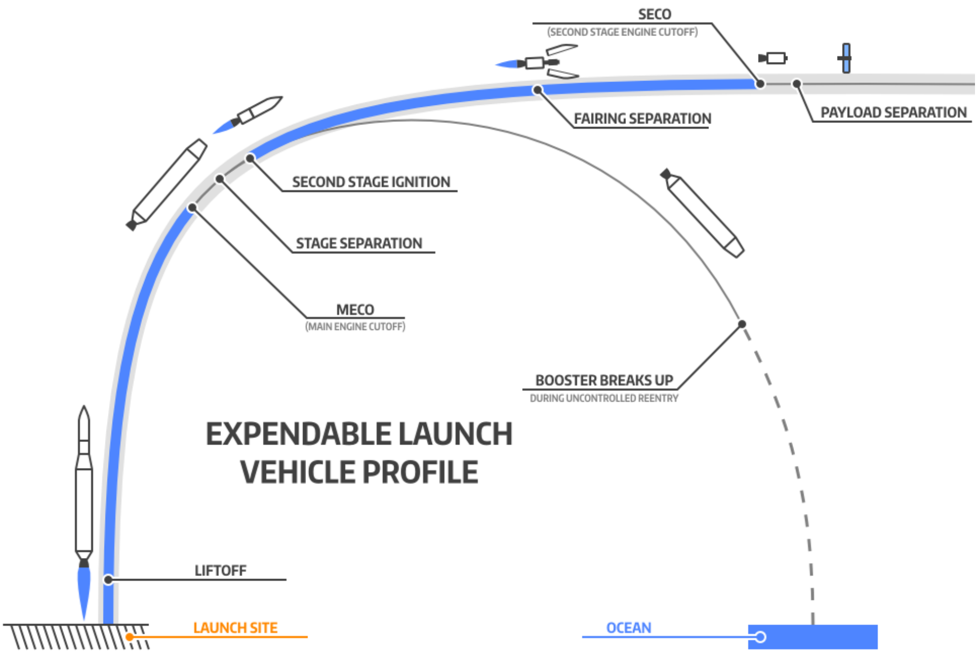
Whilst it is sufficiently fuel efficient and capable, it is still under development but should be considered in the future when LM1 is further advanced. For this reason, I will not consider this method of Launch as currently suitable, though it should not be ruled out. Lunar Mission One claims that their lander will instead likely be ‘launched into space by a medium lift rocket such as SpaceX Falcon 9’ (Lunar Mission One, 2016) ‘Falcon 9 is a two-stage rocket designed and manufactured by SpaceX for the reliable and safe transport of satellites and the Dragon spacecraft into orbit’. (Spaceflight 101, 2016).

The Dragon spacecraft is one type of payload delivery vehicle found at the top of the Falcon 9. It is mostly used for delivery of supplies to space stations where it can be accessed by astronauts upon arrival. However, it would be of no use to LM1 as its primary purpose is to carry cargo and potentially astronauts in the future. As LM1 is neither of these things, they would need to make use of the composite payload fairing, which is capable of such a task. With a height of ’13.1m’ and diameter of ‘5.2m’, (Space X, 2016a) this fairing is more than capable of transporting the LM1 craft. (Picture left; Falcon 9 Rocket. SpaceX, 2016a)

SpaceX provides two options for launch services: Either the Falcon 9, two-stage rocket, or the larger Falcon Heavy which utilizes 3 nine-engine cores. The Falcon 9 is the smaller and more cost effective way to launch and position satellites around the Earth. SpaceX claims that it is capable of hauling a Payload of up to ‘4,020 kg’ to Mars which would far exceed the fuel consumption in getting to the Moon (SpaceX, 2016b). Alternatively, the Falcon Heavy can carry three times as much (13,600kg) the same distance, and would be more suitable for a much heavier payload than the Falcon 9 is capable of holding. As a result of these differences, the Falcon Heavy service is approximately $30M million (£23 million) more expensive than the Falcon 9 is to use. LM1 lander is claimed to have a mass of about ‘two thirds of a ton before payload or fuel’. With all of this taken into consideration, it would be acceptable to assume that LM1 will comfortably fit into the Falcon 9 tolerances, and still be able to get most of the way to the Moon before fuel from LM1 itself is required (Lunar Mission One, 2016).

Stage 1

‘Falcon 9’s first stage incorporates nine Merlin engines and aluminum-lithium alloy tanks containing liquid oxygen and rocket-grade kerosene (RP-1) propellant’ (Kennedy Space Center, 2016). The initial launch profile leading up to a sub-orbital



Launch profile of Falcon 9 (Gardi & Ross, 2016)

trajector sired altitude at which to circularise, the rocket will have to begin its gravity turn at a sufficient altitude. Because

LM1 has such a low mass relative to the entire rocket, it is fairly easy to predict how the rocket will reach space without knowing precisely how much it is going to weigh.

The first stage of the Falcon 9 spacecraft incorporates 9 Merlin engines that burn through liquid oxygen and rocket-grade kerosene. According to SpaceX, the approximate burn time for this stage is a total of ‘162 seconds’ (SpaceX, 2016a). The amount of thrust produced by the engines will be subject to change as a result of differences in atmospheric pressure as the rocket ascends, but the thrust figures given by SpaceX are ‘7,607 kN’ at sea level and ‘8,227 kN’ in a vacuum (SpaceX, 2016b).

Fuel considerations also need to be taken into account for the first stage recovery system. This is ‘to allow SpaceX to return the first stage to the launch site after completion of primary mission requirements’. SpaceX do allow for excess propellant purposed for recovery to be ‘diverted for use on the primary mission objective’ (SpaceX, 2013) if required.

Stage 2

After the first stage has consumed all of the allowable fuel, the engine will cut off and the spacecraft will be on a suborbital trajectory. Shortly after, the interstage will cause stage separation followed by ignition of the second stage engine. ‘The engine is designed to burn for about six minutes, and can be shut down and restarted multiple times as needed to deliver different payloads into different orbits’ (Howells, 2009). Similar to the first stage engines, this one also burns liquid oxygen/kerosene and is much more efficient which is why the first stage booster will use Nitrogen thrusters to turn and potentially execute a short burn to correct or reposition its trajectory for landing and the rest of the fuel is used during landing.

The second stage engine will continuously fire to circularise the orbit around the Earth before shutting down to allow LM1 to maintain its Low Earth Orbit. NASA defines Low Earth Orbit as being limited to the first ‘180 to 2000 kilometres of space.’ A majority of satellites in this range take on average ‘about 99 minutes to complete an orbit’ (Earth Observatory, 2015). This gives a huge range in altitudes over which to park Lunar Mission One during these early stages of the mission. For LM1 I have calculated a suitable LEO to be approximately 190km from the Earth’s surface at a velocity of approximately 7800ms^{-1}. Although the orbital decay, a process in which the atmosphere will reduce the orbit of an object over time (Barricelli, 1971) at this low altitude is relatively high, LM1 will not be staying in this orbit long enough for it to become a particular issue.

It must also be noted that the Moon's inclination relative to the ecliptic plane, the line along which the sun travels through the sky, is '5.145°' (Williams, 2016). This is very easy to accommodate into the Launch of the rocket, assuming that the launch window is selected suitably, the 5.145° will be incorporated into the procedure with minimal expenditure of fuel, and fits well within the Falcon 9's limitations for inclination.

Overall, it takes at least 9400 ms^{-1} of Delta-V to reach this point, allowing LM1 and the second stage of the Falcon 9 to continue circling the Earth in a parking orbit, which is an orbit that a satellite can remain in for an indefinite amount of time (Waller, 2003). This is particularly useful for the fact that it gives the spacecraft a stable orbit around the Earth until the timing is right to begin the next stages of the mission.

Trans-Lunar Injection (TLI)

TLI refers to the transfer from Earth orbit to Lunar orbit (Häuplik-Meusburger & Bannova, 2016). In addition to circularising the orbit of LM1 around the Earth in LEO, the second stage contains enough fuel for the lunar transfer. SpaceX notes the typical injection orbit methods available by either Falcon 9 or Falcon Heavy are a Low Earth Orbit (including Polar/ Sun-sync), Geostationary Transfer Orbit, and an Earth Escape. With the Moon rarely being a destination of interest to private companies, it is unsurprising that a TLI is not currently included. The table below shows which launch sites make these orbit types available (SpaceX, 2016).

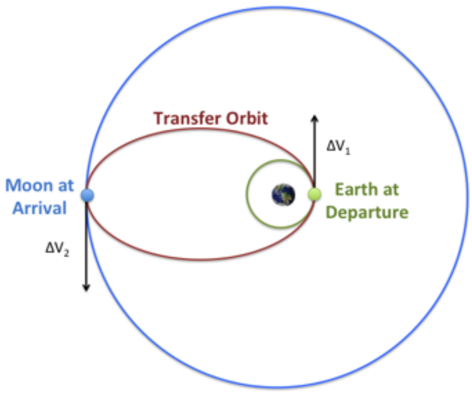
Insertion Orbit	Inclination Range	Vehicle	Launch Site(s)	Mass Capability
LEO	28.5 - 51.6 deg	Falcon 9 or Falcon Heavy	Cape Canaveral	Contact SpaceX for

LEO polar/ sun-sync	66 - 145 deg	Falcon 9 or Falcon Heavy	Vanden-berg	perfor-mance de-tails.
GTO	Up to 28.5 deg	Falcon 9 or Falcon Heavy	Cape Canaveral	
Earth Es-cape	N/A	Falcon 9 or Falcon Heavy	Cape Canaveral, Vanden-berg	

It should not be an issue that lunar transfers are not currently listed, as SpaceX currently has no experience dealing with such a manoeuvre. With further consultation with them, a solution may found, with a few potential methods of performing it.

Hohmann Transfer

The Hohmann Transfer is the simplest way to change the height of all points in an orbit, requiring only two burns of the engine. It is an effective way to bring a spacecraft to either a higher or lower orbit, and is used for a majority of missions where this is required.

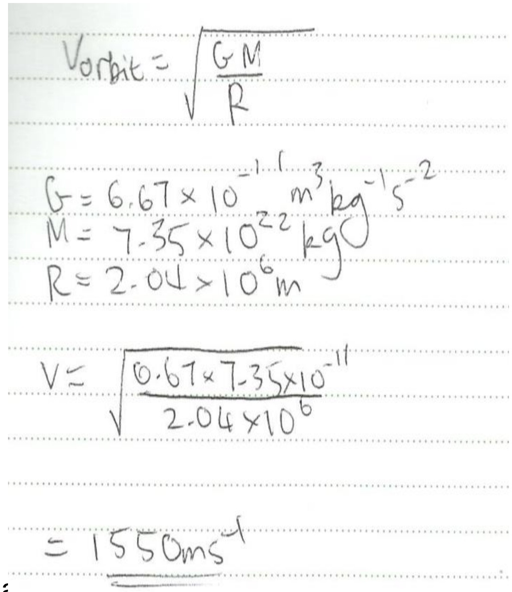


fer (Kaszynski, 2014)

In the process of getting to the Moon, the engines perform a prograde (accelerating in the direction of travel) at a given point in the LEO (MoonConnection, 2016), to bring the apoapse, which is furthest point in orbit from Earth (Bruce, 2009), approximately 3 days ahead of the Moon's orbit. The velocity must be scaled up to over 11.2 kms^{-1} order to bring the apoapse up sufficiently. Simply put, this is requires an additional of Delta-V to accelerate out of LEO. The intention of this manoeuvre is to enable the spacecraft to meet or be very near to the Moon further along in its orbit, and perform the orbit insertion from there. LM1 would move progressively further away from the Earth in an elliptical orbit, being slowed down by the pull of gravity until it reaches the apoapse.

For the Apollo missions, Biesbroek & Janin (2000), claim that 'the Moon was reached after about 70 hours'. In terms of duration, this is fairly fast and the only way to improve upon this time would be to point straight at the Moon and use excessive amounts of fuel to accelerate and decelerate which is completely wasteful, unfeasible, and unnecessary.

Once LM1 does reach the apoapse at around 380,000 km at a point very close to the Moon, it must perform a second burn of the engine, also prograde, to once again circularise/match its own orbit to the Moon's. If already within the Moon's sphere of influence (the distance from a body in which its gravitational field becomes stronger than the one travelled from (Babylon, 2016), which extends to 60,000 km from its centre then it must be ensured that the spacecraft has sufficient velocity to enable an orbit around the Moon. If outside the sphere of influence, then LM1's orbit around the Earth must be made either larger (ahead of the Moon) or smaller (behind the Moon) to enable both to come closer at a later point. I predict that at this point, the second stage will run out of fuel and require LM1 to utilize its own engines to accomplish these last few steps.



Ca
the Moon at an altitude of 300km
(Authors Own, 2016)

Arriving at the sphere of influence and descending to a distance of about 300km from the surface of the Moon would be ideal for LM1. With the Polar orbit in mind, LM1 can be made to land over one of the Moon's poles to reduce any additional orbital corrections. To circularise at this distance of 300km, I have calculated that the spacecraft would have to have a velocity of 1550 ms^{-1} at which it is a suitable altitude to reach a lower orbit and survey potential landing sites. From here it is up to the landing procedure to decide how much fuel will be used.

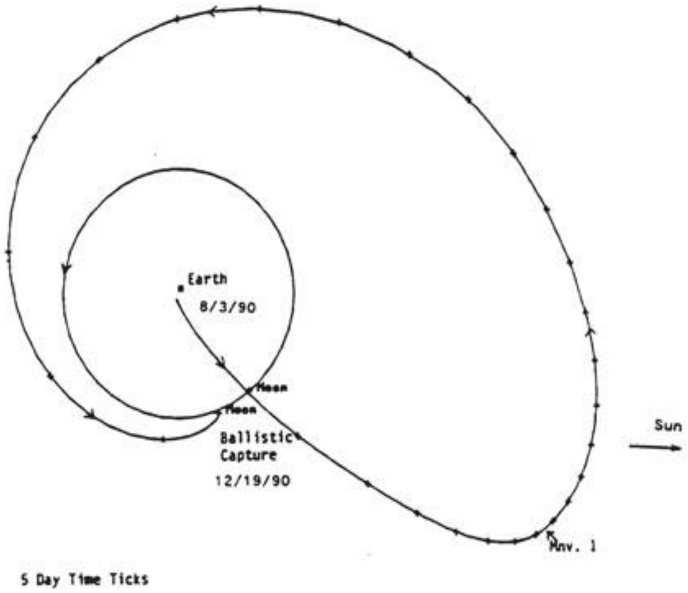
Using this method, the Delta-V required to get LM1 into this stable orbit from the Earth would be about 13-14 kms^{-1}. The Hohmann transfer itself is both effective and time tested, but when it comes to fuel economy it becomes one of the more expensive manoeuvres.

A variation on this approach would be to use the Hohmann transfer in an incremental fashion, making a number of small burns as the spacecraft keeps returning to periapse, increasing the apoapse each time. An example of this is the MORO transfer profile; 'The Translunar Orbit Injection consists of three manoeuvres of 240 m/s to increase the apogee from the GTO apogee to the Earth-Moon distance. This was done to minimise gravity losses (which occur because the thruster burns are not impulsive shots, but take a finite time during which the spacecraft has changed its position) during the burns at perigee (shortest distance from Earth). The transfer time would have been 8 days' (Biesbroek & Janin, 2000). It is essentially the same as the Hohmann transfer but slightly more efficient for lower thrust engines. The Falcon 9 second stage engine however should be more than capable to cope with a single burn at periapse.

Ballistic Capture

The second method for the TLI is a ballistic capture. The benefits of using such a transfer are that they require less fuel than the Hohmann transfer would. The Falcon 9 second stage engine 'can be restarted multiple times to place multiple payloads into different orbits' (SpaceX, 2016a) which is ideal for the conditions necessary to pull off a ballistic transfer. However, this takes a much more indirect approach than the Hohmann transfer as well as a lot more planning and calculations to work effectively.

In order to understand how this works, you must first consider the two and the three body problems. The two body problem (Kleppner & Kolenkow, 2014) states that when two bodies with a given mass interact with each other gravitationally, it is very easy to calculate how they will move relative to each other. It is made very simple by assuming one of them as completely stationary and the other in orbit around it. The Hohmann transfer is very simple as you can work with the 2 body problem accurately, for example the Earth and the spacecraft or the Moon and the spacecraft.



The three body problem is vastly more complicated as when three bodies interact with each other, it is nearly impossible to predict with 100% certainty how they will behave. This comes into play with the ballistic captures as a third body, the Sun, becomes involved. In fact this form of transfer is so complex that it should really be considered a 4 body problem involving Sun-Earth-Moon-spacecraft, but it can be approximated by using multiple 3 body solutions.

'In 1991, the Japanese mission, Muses-A, whose propellant budget did not permit it to transfer to the moon via the usual method was given a new life with an innovative trajectory design' (Koon *et al*, 2001). Since then, a newer Japanese spacecraft named Hiten, using this form of flightpath, managed to use a low energy transfer and a ballistic capture around the Moon. This works by using the Sun-Earth and Earth-Moon Lagrange points where the gravitational pull of each body is essentially cancelled out or added together by being the correct distance from each. 'It requires approximately 3150 m/s (provided by the launch vehicle) to reach the Earth–Moon L1 and L2. For another 50 m/s, you can reach the Sun–Earth L_1 and L_2' (Koon *et al*, 2001). This equates that for relatively little extra thrust, you can make your way well beyond the orbit of the Moon to the Sun-Earth Lagrange points.

A mid-course engine burn is required as the spacecraft begins to re-enter the Earth's sphere of influence. As LM1 begins to circle in back towards the Earth, specifically planning to intersect the Moon, 'Earth–Moon Lagrange point structures can be utilized for the lunar portion of the trajectory' (Pretka-Ziomek *et al*, 2013). As a result, the spacecraft can be brought into the Moon's sphere of influence at a reasonably similar velocity meaning that much less fuel is required upon circularising an orbit around the

Moon itself. This means that from LEO a Delta-V of 3200 ms^{-1} as well as a few additional small mid-course burns puts this method at a total Delta-V in the range of 13-14 kms^{-1} which in terms of fuel is a huge saving on the previous method.

Whilst a ballistic capture may seem like the obvious solution to the fuel problem, it is by far much more difficult to predict and work with. As well as this it 'depends greatly on the configuration of the specific four bodies of interest' (Koon *et al*, 2001), which does not give ideal launch window flexibility. The time that this journey takes will also be far longer as the journey is not particularly direct.

Results and Discussion

It is clear from my research that there are some aspects of the mission that are fairly certain and ronust. The need to get into a stable Low Earth Orbit to park the spacecraft for a short period of time is one of them. It is a fundamental part of many missions and will definitely be required if the timing and geometry are not correct to begin the next part of the mission. This gives the time to prepare and make any last minute changes that help ensure mission success.

As for the trans-lunar injection, it isn't completely clear which method is the best. Whilst the ballistic capture is incredibly fuel efficient, potentially saving the best part of 500+ ms^{-1} in Delta-V, it is incredibly hard to calculate, and due to the enormous distances covered by this method, it takes a significantly longer time than the reliable Hohmann transfer, giving the potential for a huge number of problems with the lander itself given that it will remain inactive for so long. Based on this information, I would determine that the Hohmann transfer marginally outweighs the ballistic in terms of reliability and short duration. The additional fuel required will certainly be costly to the LM1 budget, but with a greater flexibility in the window for making the transfer, and therefore is likely to be the better option. The ballistic capture would otherwise be better used on even smaller satellites that do not have the capacity to hold enough fuel to make the journey by conventional means. The Falcon 9 should easily make up for this by its capability for transporting loads such a great distance with its two stages.

As for the Lunar Insertion Orbit, it is a simple matter of using the fuel to circularise at an appropriate distance around the poles of the Moon once within the sphere of influence. At this point, any remaining fuel designated to orbital manoeuvres can be used up, so this is potentially one of the easiest parts of the mission.

Evaluation

If I was to continue work into this topic I would look at a greater number of ways in which to allow these low energy transfers to be used. With a greater understanding of how they work I could have planned out a specific flightpath for LM1 with a more detailed understanding of how the efficiency of different burns is altered as the spacecraft approaches the Lagrange points. Consultation with Space Agencies to weigh up the benefits and disadvantages of each manoeuvre would be invaluable to making the most cost and time effective plan for Lunar Mission One. Research into alternative fuel types and launch services could be made to compare the efficiency and the potential for the use of different launch systems.

With access to a more computer literate community, simulations could have been made to evaluate the different transfers and come up with suggestions of how they could be improved.

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