CHAPTER 1

INTRODUCTION AND EXECUTIVE SUMMARY

1.1 PURPOSE

This book provides sufficient information to answer high-level questions about the availability and performance of low-energy transfers between the Earth and Moon in any given month and year. Details are provided to assist in the construction of desirable low-energy transfers to various destinations on the Moon, including low lunar orbits, halo and other three-body orbits, and the lunar surface. Much of the book is devoted to surveys that characterize many examples of transfers to each of these destinations.

1.2 ORGANIZATION

This document is organized in the following manner. The remainder of this chapter first provides an executive summary of this book, presenting an overview of low-energy lunar transfers and comparing them with various other modes of transportation from near the Earth to lunar orbit or the lunar surface. It then provides background information, placing low-energy lunar transfers within the context of historical lunar

Low-Energy Lunar Trajectory Design. By Jeffrey S. Parker and Rodney L. Anderson

missions. The chapter describes very high-level costs and benefits of low-energy transfers compared with conventional transfers.

Chapter 2 provides information about the methods, coordinate frames, models, and tools used to design low-energy lunar transfers. This information should be sufficient for designers to reconstruct any transfer presented in this book, as well as similar transfers with particular design parameters.

Chapter 3 presents information about transfers from the Earth to high-altitude three-body orbits, focusing on halo orbits about the first and second Earth–Moon Lagrange points. The chapter includes surveys of the transfer types that exist and discussions about how to construct a particular, desirable transfer.

Chapter 4 presents information about transfers from the Earth to low-altitude lunar orbits, focusing on polar mapping orbits. The techniques presented may be used to survey and construct conventional direct lunar transfers as well as low-energy transfers.

Chapter 5 presents information about transfers from the Earth to the lunar surface, including discussions and surveys of transfers that intersect the lunar surface at a steep 90 degree (deg) angle, as well as transfers that target a shallow flight path angle. The techniques illustrated in Chapter 5 may be used to generate conventional direct transfers as well as low-energy transfers.

Chapters 3–5 also include discussions about the variations of these transfers from one month to the next. The discussions are useful for mission designers and managers to predict what sorts of transfers exist in nearly any month and what sorts of transfers are particular to specific months.

Chapter 6 discusses several important operational aspects of implementing a low-energy lunar transfer. The section begins with a discussion of the capabilities of current launch vehicles to inject spacecraft onto low-energy trajectories. The section then describes how to design a robust launch period for a low-energy lunar transfer. Additional discussions are provided to address navigation, station-keeping, and spacecraft systems issues.

1.3 EXECUTIVE SUMMARY

This book characterizes low-energy transfers between the Earth and the Moon as a resource to mission managers and trajectory designers. This book surveys and illustrates transfers between the Earth and lunar libration orbits, low lunar mapping orbits, and the lunar surface, including transfers to the Moon and from the Moon to the Earth.

There are many ways of transporting a spacecraft between the Earth and the Moon, including fast conventional transfers, spiraling low-thrust transfers, and low-energy transfers. Table 1-1 summarizes several of these methods and a sample of the missions that have flown these transfers.

The vast majority of lunar missions to date have taken quick, 3–6 day direct transfers from the Earth to the Moon. The Apollo missions took advantage of 3–3.5 day transfers: transfers that were as quick as possible without dramatically

Table 1-1 A summary of several different methods used to transfer between the Earth and the Moon.

Transfer Type	Typical Duration	Benefits	Example Missions[a]
Direct, conventional	3–6 days	Well known, quick	Apollo, *LRO*, others
Direct, staging	2–10 weeks	Quick, many launch days	*Clementine*, *CH-1*
Direct to lunar L_1	1–5 weeks	Staging at L_1	None to date
Low-thrust	Many months	Low fuel, many launch days	*SMART-1*
Low-energy	2.5–4 months	Low fuel, many launch days	*Hiten*, *GRAIL*, *ARTEMIS*

[a] Missions referred to include *Lunar Reconnaissance Orbiter (LRO)*, *Chandrayaan-1 (CH-1)*, *Small Missions for Research in Technology 1 (SMART-1)*, and *Mu Space Engineering Spacecraft (MUSES 1, Hiten)*

increasing the transfers' fuel requirements. The *Lunar Reconnaissance Orbiter (LRO)* followed a slightly more efficient 4.5-day transfer. The additional transfer duration saved fuel and relaxed the operational timeline of the mission. The Apollo missions and *LRO* had very limited launch opportunities: they had to launch within a short window each month. *Clementine* and *Chandrayaan-1* implemented phasing orbits about the Earth to alleviate this design constraint and expand their launch periods. *SMART-1* was also able to establish a wider launch period using low-thrust propulsion. The low-thrust system requires less fuel mass than conventional propulsion systems, but the transfer required significantly more transfer time than any typical ballistic transfer.

The *Gravity Recovery and Interior Laboratory (GRAIL)* mission was the first mission launched to the Moon directly on a low-energy transfer. *GRAIL*'s low-energy transfer required much less fuel than a conventional transfer, though it required a longer cruise that traveled farther from the Earth. The longer cruise (~90–114 days) made it possible to establish a wide, 3-plus week long launch period and significantly relaxed the operational timeline. Furthermore, *GRAIL* launched two satellites on board a single launch vehicle and leveraged the longer cruise to separate their orbit insertion dates by more than a day. Finally, *GRAIL*'s low-energy transfer reduced the orbit insertion change in velocity (ΔV) for each vehicle, permitting each spacecraft to perform its lunar orbit insertion with a smaller engine and less fuel.

In general, a low-energy transfer is a nearly ballistic transfer between the Earth and the Moon that takes advantage of the Sun's gravity to reduce the spacecraft's fuel requirements. The only maneuvers required are typical statistical maneuvers needed to clean up launch vehicle injection errors and small deterministic maneuvers to target specific mission features. A spacecraft launched on a low-energy lunar transfer travels beyond the orbit of the Moon, far enough from the Earth and Moon to permit the gravity of the Sun to significantly raise the spacecraft's energy. The spacecraft remains beyond the Moon's orbit for 2–4 months while its perigee radius rises. The spacecraft's perigee radius typically rises as high as the Moon's orbit, permitting the spacecraft to encounter the Moon on a nearly tangential trajectory. This trajectory has a very low velocity relative to the Moon: in some cases the spacecraft's two-body energy will even be negative as it approaches the Moon, without having performed any maneuver whatsoever. As the spacecraft approaches the Moon, it may target a trajectory to land on the Moon, to enter a low lunar orbit, or to enter any number of three-body orbit types, such as halo or Lissajous orbits. No matter what its destination, the spacecraft requires less fuel to reach it than it would following a conventional transfer.

Low-energy transfers provide many benefits to missions when compared with conventional transfers. Six example benefits include the following:

1. They require less fuel. A low-energy transfer to a lunar-libration orbit saves 400 meters per second (m/s) of ΔV and often more. This is a significant savings, which is fully demonstrated in Chapter 3. A low-energy transfer to a 100-kilometer (km) lunar orbit saves more than 120 m/s of ΔV for cases when a mission *can* use an optimized conventional transfer. The savings are far more dramatic for missions that cannot use an optimized conventional transfer.

2. Low-energy transfers are more flexible than conventional transfers and may be used to transfer spacecraft to many more orbits on a given date. It is shown in Chapter 4 that low-energy transfers may be used to reach polar orbits with any node at any arrival date—conventional transfers may only target specific nodes at any given date.

3. Low-energy transfers have extended launch periods. It requires very little fuel to establish a launch period of 21 days or more for a mission to the Moon that implements a low-energy transfer. Conventional transfers may be able to accomplish similar launch periods, but they require multiple passes through the Van Allen Belts, necessitating improved radiation protection. The low-ΔV costs of establishing a launch period for a low-energy transfer are discussed in Chapter 6.

4. Low-energy transfers have a relaxed operational timeline. Modern launch vehicles, such as the Atlas V family with their Centaur upper stages, place spacecraft on their trajectories with small errors. Missions such as *GRAIL*, which launched aboard a Delta II launch vehicle, may be able to wait 6 days or more before performing a maneuver. In fact, *GRAIL* was able to cancel the first trajectory correction maneuver (TCM) for both spacecraft; the first TCM performed was executed 20 days after launch. In this way, a spacecraft operations team has a great deal more time to prepare the spacecraft before requiring a maneuver, when compared to conventional transfers that typically require a maneuver within a day or less.

5. Low-energy transfers may place several vehicles into very different orbits at the Moon using a single launch vehicle. The *GRAIL* mission separated two lunar-orbit insertions by over a day using very little fuel. Chapter 3 illustrates how to place multiple spacecraft in many different orbit types using a single launch vehicle. This typically requires a large amount of fuel when using conventional transfers.

6. Low-energy transfers may be used to transfer a spacecraft from the Moon directly to any location on the surface of the Earth. Typical conventional transfers, for example, those used by the Apollo missions, return spacecraft to a near-equatorial landing site. Low-energy transfers may be used to target any location (such as the different hemispheres of the Utah Test and Training Range in North America and the Woomera Weapons Testing Range in South Australia) using relatively small quantities of fuel.

The typical drawbacks of low-energy transfers between the Earth and the Moon are the longer transfer durations for missions that are very time-critical and the longer link-distances, as the spacecraft travels as far as 1.5–2 million kilometers away from the Earth.

The next sections define *direct* and *low-energy* transfers to provide a clear understanding of what trajectories are presented in this book.

1.3.1 Direct, Conventional Transfers

A direct lunar transfer is a trajectory between the Earth and the Moon that requires only the gravitational attraction of the Earth and Moon. A spacecraft typically begins from a low altitude above the surface of the Earth as a result of an injection by a launch vehicle, as a result of a maneuver performed by the spacecraft, or as a result of some intermediate orbit. The spacecraft then cruises to the Moon on a trajectory that typically remains within the orbit of the Moon about the Earth. It is a trajectory whose dynamics are dominated by the gravitational attraction of the Earth and Moon, and all other forces (such as the Sun or any spacecraft events) may be considered to be perturbations. The spacecraft then enters some orbit about the Moon via a maneuver. Direct transfers may be constructed from the Moon to the Earth in much the same way as they are constructed to the Moon.

Figure 1-1 illustrates a 3-day transfer nearly identical to the one the *Apollo 11* astronauts used to go from the Earth to the Moon in 1969 [1]. The mission implemented a low-Earth parking orbit with an inclination of approximately 31.38 deg. From there, the launch vehicle was required to attain a trans-lunar injection energy (C_3) of approximately -1.38 km^2/s^2 to reach the Moon in approximately 3.05 days. Upon arrival at the Moon, the vehicle injected into an elliptical orbit with a periapse altitude of approximately 110 km and an apoapse altitude of approximately 310 km, followed soon after by a circularization maneuver [1]. In order to compare the *Apollo 11* transfer with the transfers in the surveys presented here, the *Apollo 11* transfer would have a velocity of approximately 2.57 kilometers per second (km/s) at an altitude of 100 km above the mean lunar surface, requiring a hypothetical, impulsive ΔV of approximately 0.94 km/s to insert into a circular 100-km orbit.

Direct transfers may be constructed between the Earth and the Moon with durations as short as hours or as long as a few weeks. In general, the most fuel-efficient direct transfers require about 4.5 days of transfer duration. Any longer duration typically sends the spacecraft beyond the orbit of the Moon before it falls back and encounters the Moon.

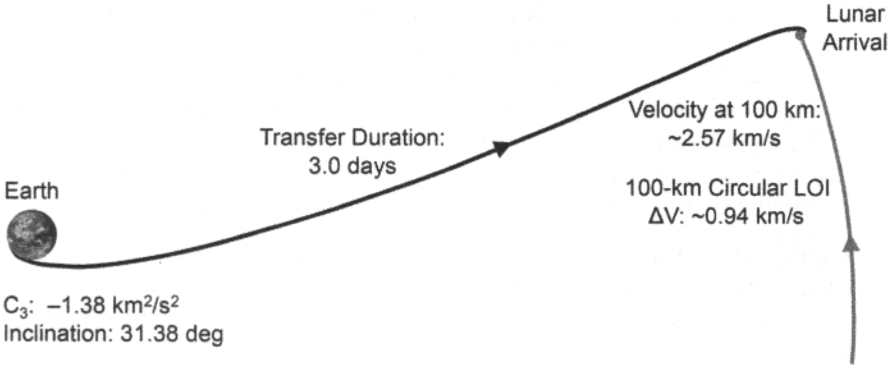

Figure 1-1 A modified version of the Apollo 11 Earth–Moon transfer, as if it had performed an impulsive lunar-orbit insertion (LOI) maneuver directly into a circular 100-km lunar orbit [2]. (Copyright © 2011 by American Astronautical Society Publications Office, all rights reserved, reprinted with permission of the AAS.)

Direct transfers may also be constructed between the Earth and lunar libration orbits for similar amounts of fuel as required to transfer directly to low lunar orbits. The launch energy requirement is very similar for missions to the Moon, to Lagrange 1 (L_1), and to Lagrange 2 (L_2), and to a first order may be treated as equal. A direct transfer requires 400–600 m/s of ΔV to insert into a lunar libration orbit about either L_1 or L_2, though a powered lunar flyby en route to a libration orbit about L_2 may be used to reduce the total transfer cost by 100–200 m/s. These transfers are examined in Chapter 3.

Several missions have added Earth phasing orbits to their mission itineraries, such that they launch into a high-altitude, temporary Earth orbit and remain in that orbit for several orbits before arriving at the Moon. A mission designer may add these orbits to a flight plan for several reasons. First, they may be used to establish an extended launch period, since the mission planners can adjust the size of the phasing orbits to compensate for varying launch dates. Second, they may be used to reduce the operational risk of the mission by increasing the amount of time between each maneuver en route to the Moon. They may also be used if the launch vehicle is not powerful enough or accurate enough to send the spacecraft directly to the Moon, such as *Chandrayaan-1* [3]. Drawbacks of Earth phasing orbits include additional passes through the Van Allen Belts and an extended transfer duration.

1.3.2 Low-Energy Transfers

Low-energy transfers take advantage of the Sun's gravity to reduce the transfer fuel costs. They involve trajectories that take the spacecraft beyond the orbit of the Moon, where the Sun's gravity becomes more influential. The Sun's gravity works slowly and steadily, gradually raising the spacecraft's periapse altitude until it has risen to the altitude of the Moon's orbit about the Earth. When the spacecraft falls back toward the Earth, it arrives at the Moon with a velocity that closely matches the Moon's orbital velocity. The result is that the spacecraft's lunar orbit insertion requires much less fuel than required by a conventional, direct lunar transfer. Figure 1-2 illustrates an example 84-day low-energy transfer that arrives at the Moon when the Moon is at its first quarter. More explanation of these transfers is provided in Section 1.7 and in later chapters.

Low-energy transfers typically travel far beyond the orbit of the Moon; hence, they may be designed to take advantage of one or more lunar flybys on their outbound segment. The lunar flybys may be used to reduce the injection energy requirements, or to change the spacecraft's orbital plane, similar to the flight of each of the two *Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun* (*ARTEMIS*) spacecraft [4]. If a mission takes advantage of a lunar flyby immediately after launch, it may be useful to add one or more Earth phasing orbits into the design, as described above.

1.3.3 Summary: Low-Energy Transfers to Lunar Libration Orbits

Low-energy transfers may be used to save a great deal of fuel when a mission's destination is a lunar libration orbit, such as a halo orbit, a Lissajous orbit, or

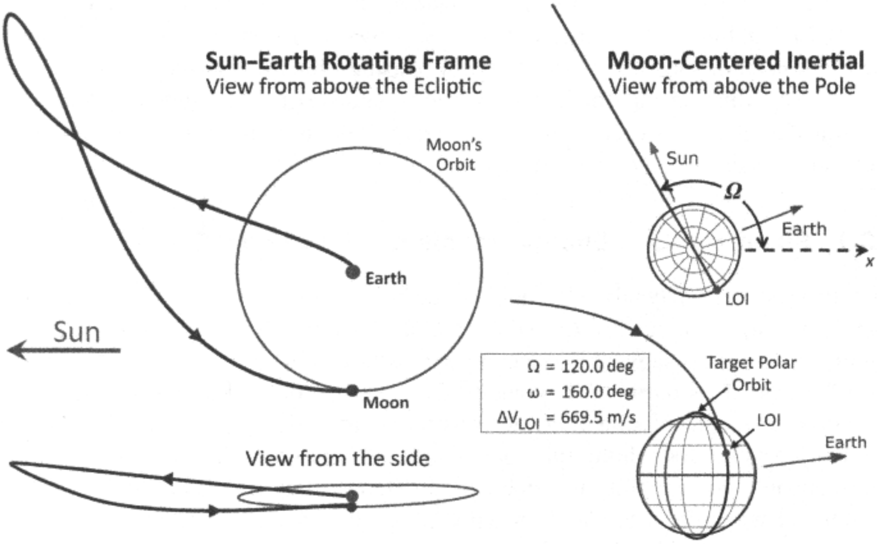

Figure 1-2 An example 84-day low-energy lunar transfer to a low, polar lunar orbit [2]. (Copyright © 2011 by American Astronautical Society Publications Office, all rights reserved, reprinted with permission of the AAS.)

some other three-body orbit. Many studies have demonstrated practical applications of lunar libration orbits, including locations for communication satellites [5–7], navigation satellites [8–13], staging orbits [14–18], and science orbits [4, 19]. The *ARTEMIS* mission took advantage of the geometries of several orbits about both the lunar L_1 and L_2 points, and it used two different low-energy transfers to arrive at those orbits.

Chapter 3 presents a full study of the characteristics and performance of low-energy transfers to lunar libration orbits. The results demonstrate that a typical transfer requires 70–120 days to travel from Earth departure to an arrival state that is within 100 km of the target libration orbit. The transfers arrive asymptotically, such that they do not require any insertion maneuver. This is an extraordinary benefit: it saves a mission upwards of 500 m/s of ΔV when compared to conventional, direct transfers to lunar libration orbits. The typical transfers studied in Chapter 3 depart the Earth with a C_3 of -0.7 to -0.3 km^2/s^2, which is higher than the conventional transfer that has a C_3 of approximately -2.0 km^2/s^2, but the low-energy transfer requires only small TCMs after the Earth-departure maneuver. Studies show (Section 6.5) that two or three deterministic maneuvers with a total of only ~70 m/s of ΔV may be used to depart the Earth from a specific inclination (such as 28.5 deg), and from any day within a 21-day launch period, and arrive at a particular location in a specified libration orbit.

Figures 1-3 and 1-4 illustrate two example direct transfers and two example low-energy transfers to lunar libration orbits, respectively. One can see that these transfers are ballistic in nature: they require a standard trans-lunar injection maneuver, a few TCMs, and an orbit insertion maneuver (which is essentially zero for the low-energy transfers). One may also add Earth phasing orbits and/or lunar flybys to the trajectories, which change their performance characteristics. Figure 1-5 illustrates two transfers that a spacecraft may take to depart the libration orbit using minimal fuel and transfer to a low lunar orbit or to the lunar surface.

1.3.4 Summary: Low-Energy Transfers to Low Lunar Orbits

Robotic spacecraft may take advantage of the benefits of a low-energy transfer when transferring to a low lunar orbit, such as *GRAIL*'s target lunar orbit. The transfer duration is about the same as a low-energy transfer to a lunar libration orbit, namely, 70–120 days. This duration is typically far too long for human occupants, unless the purpose of the mission is to demonstrate a long deep-space transfer. There are many benefits for robotic missions, including smaller orbit insertion maneuver requirements, the capability to establish an extended launch period, and a relaxed operational schedule. The *GRAIL* mission took advantage of these benefits, as well as the characteristic that it requires very little ΔV to separate the two spacecraft from their joint launch. *GRAIL*'s two spacecraft flew independently to the Moon and arrived 25 hours apart: a feat that requires a great deal more ΔV and/or operational complexity when implementing direct lunar transfers. Low-energy transfers may also access a much broader range of lunar orbits for a particular arrival date than direct transfers.

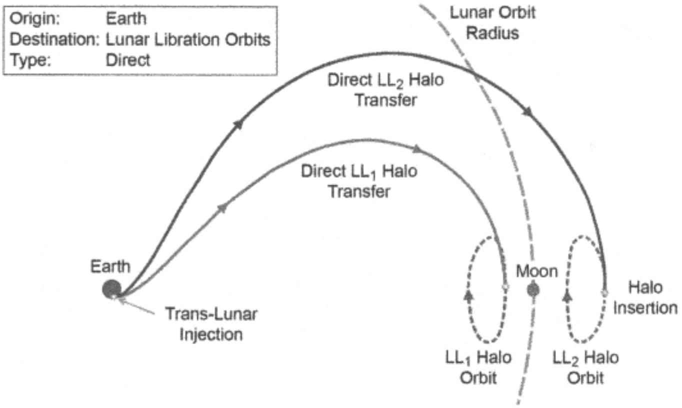

Figure 1-3 The profile for a simple, direct transfer from the Earth to a lunar libration orbit about either the Earth–Moon L_1 or L_2 point, viewed from above in the Earth–Moon rotating coordinate frame.

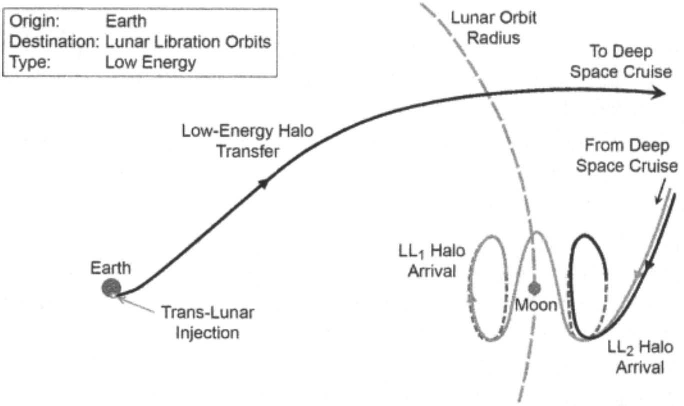

Figure 1-4 The profile for a simple, low-energy transfer from the Earth to a lunar libration orbit about either the Earth–Moon L_1 or L_2 point, viewed from above in the Earth–Moon rotating coordinate frame.

Chapter 4 presents a full study on the characteristics and performance of low-energy transfers to low lunar, polar orbits. The examination uses 100-km circular, polar orbits as the target orbits to simplify the trade space. It remains relevant to practical mission design since many spacecraft missions have inserted into very similar orbits, including *Lunar Prospector, Kaguya/ Selenological and Engineering Explorer (SELENE), Chang'e 1, LRO,* and *GRAIL*, among others. The results of the study indicate that low-energy transfers typically depart the Earth with an injection C_3 of -0.7 to -0.3 $\mathrm{km^2/s^2}$, much like low-energy transfers to lunar libration orbits,

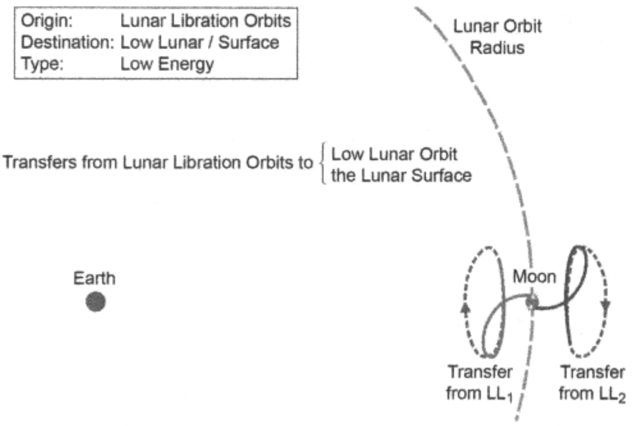

Figure 1-5 The profile for a simple, low-energy transfer from a libration orbit to either a low lunar orbit or the surface of the Moon, viewed from above in the Earth–Moon rotating coordinate frame.

and require 70–120 days to reach the Moon. A spacecraft may implement a lunar flyby on the outbound segment to reduce the launch energy requirement, but such an event would increase the complexity and operational risk of the mission. When the spacecraft arrives at the Moon, it arrives traveling at a slower relative speed than if it had used a direct lunar transfer. The examination shows that the lunar-orbit insertion maneuver is at least 120 m/s smaller for any low-energy mission; the ΔV savings are often much greater.

Low-energy transfers may also be used in such a way that a spacecraft transfers to a lunar libration orbit, or some other three-body orbit, before transferring to the target orbit. This strategy was used in the *ARTEMIS* mission and has been used in a number of spacecraft proposals.

Figure 1-6 illustrates an example direct transfer and an example low-energy transfer to two low lunar orbits. The transfers are very similar to those presented in the previous section, except of course that these target low lunar orbits instead of lunar libration orbits.

1.3.5 Summary: Low-Energy Transfers to the Lunar Surface

Low-energy transfers from the Earth to the lunar surface may be constructed in much the same way as transfers to low lunar orbit. They have the same sorts of benefits and drawbacks as other low-energy transfers.

Chapter 5 presents a full study on the characteristics and performance of low-energy transfers to the lunar surface. There are two main classes of missions studied: those that arrive at the surface with a high impact angle and those that arrive at the surface with a shallow flight path angle. The shallow angles are useful for missions that aim to land on the surface, and then it is useful that the low-energy transfers

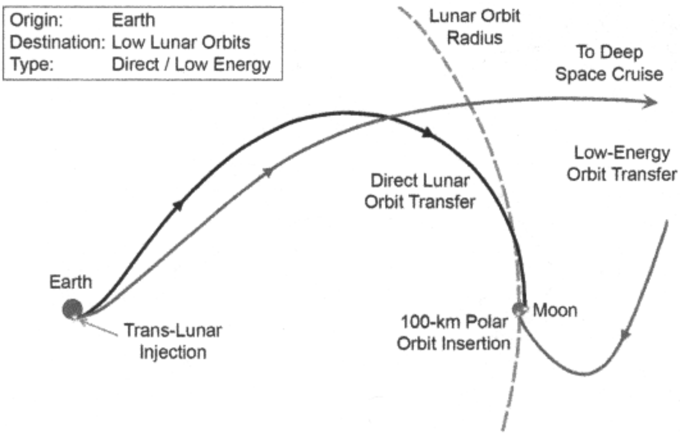

Figure 1-6 The profiles for both a direct and a low-energy transfer from the Earth to a low lunar orbit.

yield trajectories that arrive at the surface with lower velocities. The steeper arrival conditions are useful for lunar impactors, such as the *Lunar Crater Observatory and Sensing Satellite (LCROSS)*. In this case, higher velocities are typically preferred. Low-energy transfers may not result in the highest impact velocities achievable, but they do offer the capability of targeting any location on the surface of the Moon with ease.

As with the low-energy transfers studied in Chapters 3 and 4, the typical transfers to the lunar surface require 70–120 days. They typically depart the Earth with C_3 values between –0.7 and –0.3 kilometers squared per square second (km^2/s^2) and only require small trajectory correction maneuvers after launch. The same sort of two- or three-burn strategies may be used to target a particular low-energy transfer from a specified low Earth parking orbit, and from any day within a 21-day launch period.

The lunar surface may also be accessed from a lunar libration orbit or from a low lunar orbit. Hence, a mission may implement a low-energy transfer to either type of orbit studied in Chapters 3 or 4 and then follow a transfer to the lunar surface. This sort of trajectory design is also studied in Chapter 5.

Figure 1-7 illustrates an example direct transfer and an example low-energy transfer to the lunar surface. Again, the transfers are very similar to those presented in the previous two sections, except (of course) that these target the lunar surface.

1.4 BACKGROUND

This section reviews historical lunar missions as a reference for the discussions about designing future lunar missions, including future missions that use direct transfers as well as low-energy transfers. Nearly one hundred spacecraft have flown conventional,

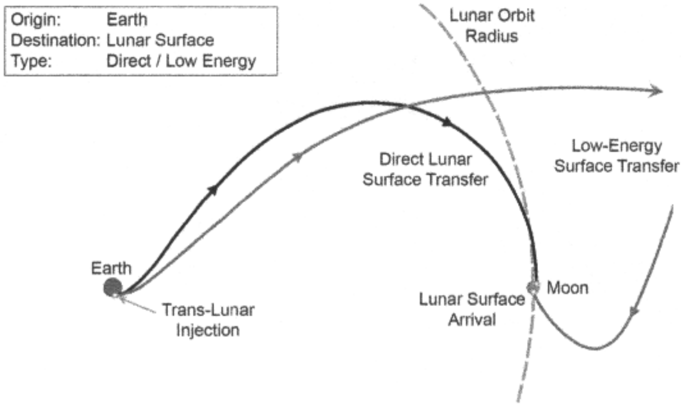

Figure 1-7 The profiles for both a direct and a low-energy transfer from the Earth to the lunar surface. Transfers may be constructed to arrive with a shallow or steep flight path angle.

direct transfers between the Earth and the Moon, including the Union of Soviet Socialist Republics' (USSR's) Luna spacecraft, the USA's Apollo spacecraft, and the most recent international missions. Only five spacecraft have flown low-energy lunar transfers, though several others have followed low-energy transfers to other destinations near the Earth. The complexity of lunar missions has gradually grown, as has the need to save money and collect a greater scientific return using less fuel. Modern flight operations, spacecraft hardware, and infrastructure have opened the door to low-energy techniques as a method to reduce costs.

The first two missions to implement low-energy transfers—*Hiten* and *ARTEMIS*—demonstrated the technique as a method to extend their missions to the Moon, despite not having the fuel to reach lunar orbit using conventional techniques. The *GRAIL* mission, launched on September 10, 2011, was the first mission to implement a low-energy lunar transfer as part of its primary mission. The *GRAIL* mission benefited from its low-energy route to the Moon in more ways than just saving fuel. It is fully expected that more missions will follow this lead, and low-energy transfers will become common among lunar missions.

1.5 THE LUNAR TRANSFER PROBLEM

Soon after the dawn of the Space Age, people were designing trajectories for spacecraft to travel to the Moon [20, 21]. In fact, not even a full year had elapsed since the launch of *Sputnik* (October 4, 1957) before the United States attempted to launch the *Pioneer 0* probe to the Moon (August 17, 1958). The first probes designed to explore the Moon were plagued with launch vehicle failures, including four Pioneer failures by the United States and three Luna failures by the Soviet Union. It was not until 1959 that *Luna 1* finally flew by the Moon. Later in 1959, *Luna 2* became the first probe to impact the Moon.

As technology improved, spacecraft were able to fly to the Moon using less fuel. Several general bounds exist that limit the movement of a spacecraft in the Earth–Moon system when other perturbations, such as the Sun's gravity, are ignored. Research in the circular restricted three-body problem (examined in Section 2.6.2) reveal that a spacecraft with enough energy to reach the Earth–Moon L_1 point has the minimum energy required to transfer to the Moon, without considering other perturbations. Sweetser computed that the theoretical minimum ΔV that a spacecraft would require to travel from a 167-km altitude circular orbit at the Earth to a 100-km altitude circular orbit at the Moon, just passing through L_1, is approximately 3.721 km/s [22]. Actual trajectories have since been computed that approach this theoretical minimum [23].

Early investigations concluded that it is impossible to launch from the Earth and arrive at the Moon such that the spacecraft becomes captured without performing a maneuver [21]; however, these analyses did not include the effects of the Sun's gravity. As early as 1968, Charles Conley began using dynamical systems methods to explore the construction of a theoretical trajectory that could become temporarily captured by the Moon without performing a capture maneuver [24]. A spacecraft with the proper energy could target the neck region near one of the collinear libration points in the Earth–Moon system (see Section 2.6.2). A planar periodic orbit exists in each of those regions that acts as a separatrix, separating the interior of the Moon's region from the rest of the Earth–Moon region. Conley's method implemented dynamical systems techniques to construct the transfer by targeting the gateway periodic orbit. His transfers were restricted to the Moon's orbital plane.

In the late 1980s and early 1990s, Belbruno and Miller began developing a method to construct lunar transfers using a new technique, which they have referred to as the weak stability boundary (WSB) theory [25–27]. The method involves targeting the region of space that is in gravitational balance between the Sun, Earth, and Moon, without involving any three-body periodic orbits or other dynamical structures. Ballistic capture occurs when the spacecraft's two-body energy becomes negative, as described by Yamakawa [28, 29]. In 1991, the Japanese mission *Hiten/MUSES-A* used the effects of the Earth, Moon, and Sun for its transfer to the Moon [30].

In the early 2000s, Ivashkin also developed a method to construct transfers between the Earth and Moon using the Sun's gravitational influence [31–34]. His methods involve beginning from a low lunar orbit, or from the surface of the Moon, and numerically targeting trajectories that depart from the Moon in the direction of the Earth's L_1 or L_2 points. A spacecraft on such a trajectory departs from the Moon with a negative two-body energy with respect to the Moon, but as it climbs away from the Moon, it gains energy from the effect of the Earth's and Sun's gravity. Eventually, it gains enough energy to escape the Moon's vicinity. The trajectory is then targeted such that it lingers near the chosen Lagrange point long enough to allow the Sun to lower the perigee radius of the next perigee passage down to an altitude of approximately 50 km.

In the mid 1990s, other methods were developed to construct a lunar transfer that takes advantage of the chaos in the Earth–Moon three-body system. Bollt and Meiss constructed a trajectory that sent a spacecraft into an orbit without sufficient energy to immediately reach the Moon, but with enough to get close enough to become substantially perturbed by the Moon [35]. Using a series of four very small maneuvers, the spacecraft could then hop between nearby trajectories in the chaotic sea of possible trajectories to become captured by the Moon using far less energy than standard direct transfers. In 1997, Schroer and Ott reduced the time of transfer for the chaotic lunar transfer by targeting specific three-body orbits near the Earth [36]. The total cost remained approximately the same as the transfer constructed by Bollt and Meiss, but the transfer duration was reduced from approximately 2.05 years to 0.8 years.

In 2000, Koon et al. [37, 38] constructed a planar lunar transfer that was almost entirely ballistic using the techniques involved in Conley's method [38]. Following Conley, Koon et al. [37] observed that the planar libration orbits act as a gateway between the interior and exterior regions of space about the Moon. Koon et al. [37, 38] constructed a trajectory that targets the interior of the stable invariant manifold of a planar libration orbit about the Earth–Moon L_2 point. Once inside the interior of the stable manifold, the spacecraft ballistically arrives at a temporarily captured orbit about the Moon. Many authors have debated what it means to be *temporarily captured* at the Moon; Koon et al., define a similar term, "ballistically captured" to be a trajectory that comes within the sphere of influence of the Moon and revolves about the Moon at least once [38].

Further advances have been made since 2004 to apply dynamical systems theory to the generation of three-dimensional low-energy lunar transfers [39–44]. Parker mapped out numerous families of low-energy transfers, illuminating different geometries that are available for spacecraft to travel to the Moon and arrive in lunar libration orbits without requiring any capture maneuver [2, 45–47]. Several authors have begun applying low-thrust techniques to further improve low-energy transfers, including transfers from the Earth to the Moon and transfers from one libration orbit to another [48–55]. In 60 years, research has advanced the knowledge of lunar transfers from the early spacecraft missions that implemented direct lunar transfers to modern analyses that reveal maps of entire families of low-energy transfers to the Moon.

1.6 HISTORICAL MISSIONS

Many historical missions have taken direct transfers from the Earth to the Moon, including a large number of spacecraft in the Luna, Zond, Ranger, Surveyor, Lunar Orbiter, and Apollo programs. A few of these missions implemented direct transfers back to the Earth again: most notably *Luna-16* and the nine Apollo missions that ventured to the Moon and returned. Several other missions have also flown direct transfers since the 1960s, and they are summarized below.

Low-energy lunar transfers are closely related to low-energy transfers in the Sun–Earth system, as is described later in this book. Since the 1970s, several spacecraft have been placed on three-body trajectories in the Sun–Earth system to conduct their scientific and technological missions, including *International Sun–Earth Explorer-3 (ISEE-3), Solar and Heliospheric Observatory (SOHO), Advanced Composition Explorer (ACE), Wind, Wilkinson Microwave Anisotropy Probe (WMAP)*, and *Genesis,* among others. Three spacecraft are known to have followed three-body trajectories in the Earth–Moon system, including *SMART-1* and the two *ARTEMIS* spacecraft. Between 1991 and 2011, five spacecraft have traversed low-energy transfers from the Earth to the Moon, including *Hiten/MUSES-A* in 1991, the two *ARTEMIS* spacecraft in 2010 and the two *GRAIL* spacecraft in 2011. A brief summary of each of these missions will be presented here.

1.6.1 Missions Implementing Direct Lunar Transfers

Table 1-2 summarizes many historical missions that have taken direct lunar transfers, noting their launch date and transfer duration, among other things. One notices that early missions implemented very quick transfers that required fewer than 1.5 days to reach the Moon. These involved lunar flybys or impacts, with no intention of inserting into orbit or landing softly. Indeed, their velocities at the Moon would be quite high. The first soft landing was performed by the Soviet Union's *Luna 9*, which took a 79-hour transfer to the Moon. The first robotic sample return attempt was performed by the Soviet Union's *Luna 15*, which took a 101.6-hour transfer to the Moon: longer to save fuel mass so that it would be capable of returning to the Earth. *Luna 16* was the first successful robotic sample return, taking a 105.1-hour lunar transfer. The first human landing, and first successful sample return was performed earlier, by *Apollo 11*. The direct transfer that *Apollo 11* took required about 73 hours, which was shorter in time and required more fuel, but required less total consumable mass than a longer transfer since the mission involved human occupants.

1.6.2 Low-Energy Missions to the Sun–Earth Lagrange Points

ISEE-3. On August 12, 1978, the *International Sun–Earth Explorer 3 (ISEE-3)* spacecraft was launched and placed in a halo orbit about the Sun–Earth L_1 point. It was the first spacecraft to be inserted into an orbit about a Lagrange point. On June 10, 1982, the spacecraft began performing 15 very small maneuvers to guide it on a series of lunar flybys. Its fifth and final lunar flyby was performed on December 22, 1983, coming within 120 km of the lunar surface. The lunar flyby ejected the spacecraft from the Earth–Moon system and it entered a heliocentric orbit. The spacecraft was renamed the *International Cometary Explorer (ICE)* as it readied for its encounter with the comet Giacobini-Zinner. On June 5, 1985, *ICE* entered the comet's tail and collected scientific information about the tail. *ICE* is expected to return to the vicinity of the Earth in 2014, when it may be captured and brought back to Earth, or repurposed for another comet observation mission. Figure 1-8 shows a plot of the trajectory of *ISEE-3/ICE* [60, 61].

Table 1-2 The transfer durations, among other information, of several historical missions that have implemented direct lunar transfers [56–59].

Launch Date	Spacecraft	Nation[a]	Transfer Duration	Notes
There were 24 successful Soviet Luna missions; examples include:				
2 Jan. 1959	*Luna 1*	USSR	34 hr (1.42 days)	First lunar flyby (5995 km)
12 Sept. 1959	*Luna 2*	USSR	33.5 hr (1.40 days)	First lunar impact (29.10 N, 0.00 E)
4 Oct. 1959	*Luna 3*	USSR	60 hr (2.50 days)	Flyby (6200 km)
2 Apr. 1963	*Luna 4*	USSR	77.3 hr (3.22 days)	Flyby (8336.2 km)
9 May 1965	*Luna 5*	USSR	~83 hr (3.4 days)	First soft-landing attempt; impact (31 S, 8 W)
31 Jan. 1966	*Luna 9*	USSR	79 hr (3.29 days)	First soft landing (7.08 N, 64.37 W)
31 Mar. 1966	*Luna 10*	USSR	78.8 hr (3.29 days)	First orbiter
13 July 1969	*Luna 15*	USSR	101.6 hr (4.23 days)	First sample return attempt
12 Sep. 1970	*Luna 16*	USSR	105.1 hr (4.38 days)	First sample return (101 grams)
9 Aug. 1976	*Luna 24*	USSR	103.0 hr (4.29 days)	Sample return, landing within 1 km of *Luna 23* (170 grams returned)
There were eight Soviet Zond missions; little accurate information is available.				
18 July 1965	*Zond 3*	USSR	33 hr (1.38 days)	Flyby (9200 km)
14 Sept. 1968	*Zond 5*	USSR	~3.4 days	First circumlunar return
There were nine American Ranger missions; examples include:				
26 Jan. 1962	*Ranger 3*	USA	2–3 days	Flyby (~36,800 km)
23 Apr. 1962	*Ranger 4*	USA	64 hr (2.67 days)	Impact (15.5 S, 130.7 W)
18 Oct. 1962	*Ranger 5*	USA	2–3 days	Flyby (725 km)
30 Jan. 1964	*Ranger 6*	USA	65.5 hr (2.73 days)	Impact
28 July 1964	*Ranger 7*	USA	68.6 hr (2.86 days)	Impact (10.70 S, 20.67 W)
17 Feb. 1965	*Ranger 8*	USA	64.9 hr (2.70 days)	Impact (2.71 N, 24.81 E)
21 Mar. 1965	*Ranger 9*	USA	64.5 hr (2.69 days)	Impact (12.91 S, 2.38 W)
There were seven American Surveyor missions, including:				
30 May 1966	*Surveyor 1*	USA	63 hr (2.63 days)	Landed (2.45 S, 43.21 W)
20 Sept. 1966	*Surveyor 2*	USA	~1.9 days	Impact (5.5 N, 12 W)
17 Apr. 1967	*Surveyor 3*	USA	64.5 hr (2.69 days)	Landed (3.01 S, 23.34 W)
14 July 1967	*Surveyor 4*	USA	~2.6 days	Impact (0.4 N, 1.33 W)
8 Sept. 1967	*Surveyor 5*	USA	64.8 hr (2.70 days)	Landed (1.41 N, 23.18 E)
7 Nov. 1967	*Surveyor 6*	USA	65.0 hr (2.71 days)	Landed (0.49 N, 1.4 W); First powered take-off
7 Jan. 1968	*Surveyor 7*	USA	66.0 hr (2.75 days)	Landed (40.86 S, 11.47 W)
There were five American Lunar Orbiter missions; examples include:				
10 Aug. 1966	*Lunar Orbiter 1*	USA	91.6 hr (3.82 days)	Orbiter
6 Nov. 1966	*Lunar Orbiter 2*	USA	92.5 hr (3.85 days)	Orbiter
5 Feb. 1967	*Lunar Orbiter 3*	USA	92.6 hr (3.86 days)	Orbiter
There were 9 American Apollo missions that orbited or orbited and landed on the Moon; examples include:				
21 Dec. 1968	*Apollo 8*	USA	66.3 hr (2.76 days)	First manned lunar orbiter
18 May 1969	*Apollo 10*	USA	73.3 hr (3.05 days)	Orbit and return
16 July 1969	*Apollo 11*	USA	73.1 hr (3.04 days)	First manned landing
7 Dec. 1972	*Apollo 17*	USA	83.0 hr (3.46 days)	Final manned landing 35-km traverse, 110.5 kg returned

[a] Union of Soviet Socialist Republic (USSR) and United States of America (USA)

Table 1-2 Continued.

Launch Date	Spacecraft	Nation	Transfer Duration	Notes
	Additional missions that have implemented direct transfers include:			
3 Mar. 1959	*Pioneer 4*	USA	29.3 hr (1.22 days)	Flyby, first USA spacecraft to reach escape velocity
19 July 1967	*Explorer 35*	USA	~2 days	Orbiter
10 June 1973	*Explorer 49*	USA	113.1 hr (4.71 days)	Orbiter
25 Jan. 1994	*Clementine*	USA	~4 days + 12 days phasing	Orbiter
24 Dec. 1997	*Asiasat 3* / HGS-1	China	~4.5 days	2 lunar flybys en route to GEO
7 Jan. 1998	*Lunar Prospector*	USA	105 hr (4.38 days)	Orbiter
26 Oct. 2006	*STEREO Ahead*	USA	85 hr (3.54 days) + 47 days phasing	1 lunar flyby
26 Oct. 2006	*STEREO Behind*	USA	83 hr (3.46 days) + 47 days phasing	2 lunar flybys
14 Sept. 2007	*Kaguya*/SELENE	Japan	127 hr (5.29 days)	Orbiter
24 Oct. 2007	*Chang'e 1*	China	~120 hr (~5 days) + 7 days phasing	Orbiter
22 Oct. 2008	*Chandrayaan-1*	India	107.9 hr (4.50 days) + 13 days phasing	Orbiter/impactor
18 June 2009	*LRO/LCROSS*	USA	108 hr (4.5 days)	Orbiter/impactor
1 Oct. 2010	*Chang'e 2*	China	112.1 hr (4.7 days)	Orbiter

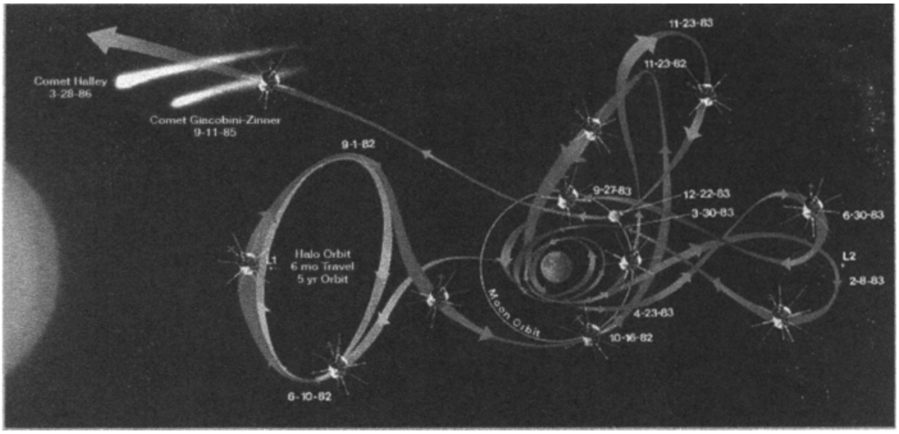

Figure 1-8 The trajectory of *ISEE-3 / ICE* [62]. (See color insert.)

Wind. The *Wind* mission was launched on November 1, 1994, and placed in a halo orbit about the Sun–Earth L_1 point. Its scientific objectives were to characterize the solar wind using a variety of particle and field measurements, all of which complemented several other spacecraft in a variety of other orbits, including the *Polar* and *Geotail* satellites, as part of the International Solar-Terrestrial Physics (ISTP) Science Initiative. After several years of measurements from the Sun–Earth L_1 environment, *Wind*'s orbit was altered to give it access to new areas in the near-Earth environment, including a campaign of "petal orbits" to send it out of the ecliptic plane (1998–1999), a lunar backflip (April, 1999), several revolutions about a distant prograde orbit (2001–2003), and a complex orbit that involved repeated lunar flybys and excursions out beyond the Sun–Earth L_1 and L_2 points (2003–2006). The first part of *Wind*'s trajectory resembles the first part of *ISEE-3*'s trajectory shown in Fig. 1-8. Figure 1-9 illustrates *Wind*'s orbits in the Sun–Earth system from 2003 through 2006 [63], illustrating a unique aspect of its low-energy mission design.

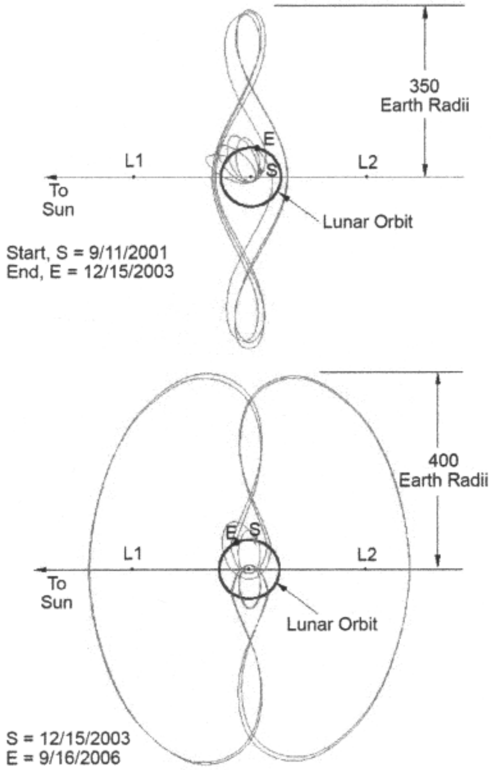

Figure 1-9 The trajectory of *Wind* from 2003 through 2006, viewed from above in the Sun–Earth rotating frame [63].

SOHO. The *Solar and Heliospheric Observatory (SOHO)* was launched on December 2, 1995, on a path taking it directly toward a libration orbit about the Sun–Earth L_1 point. On March 17, 1996, SOHO performed a small orbit insertion maneuver to formally enter the quasi-halo L_1 orbit 1.5 million kilometers away from the Earth. The L_1 halo orbit is ideal for the observatory because it provides an unobstructed view of the Sun on one side and a near-constant view of the Earth on the other side. Hence, it can collect scientific data about the Sun continuously, while being able to communicate with the Earth at any time. Figure 1-10 shows a plot of the trajectory that *SOHO* used to transfer to its halo orbit [64–67].

ACE. In 1997, the *Advanced Composition Explorer (ACE)* was launched and placed in a Lissajous orbit about the Sun–Earth L_1 point. Its mission, much like *SOHO*'s, is dedicated to collecting energetic particles to study the solar corona, interplanetary medium, solar wind, and cosmic rays. Its transfer appears very similar to *SOHO*'s transfer, shown in Fig. 1-10 [68, 69].

WMAP. Launched on June 30, 2001, the *Wilkinson Microwave Anisotropy Probe (WMAP)* is currently residing in a small-amplitude Lissajous orbit about the Sun–Earth L_2 point. From this orbit, *WMAP* continues to measure cosmic background radiation, unobstructed by the radiation originating from the Sun, Earth, or Moon. Figure 1-11 shows a plot of the trajectory that *WMAP* used to reach its libration orbit about L_2 [70].

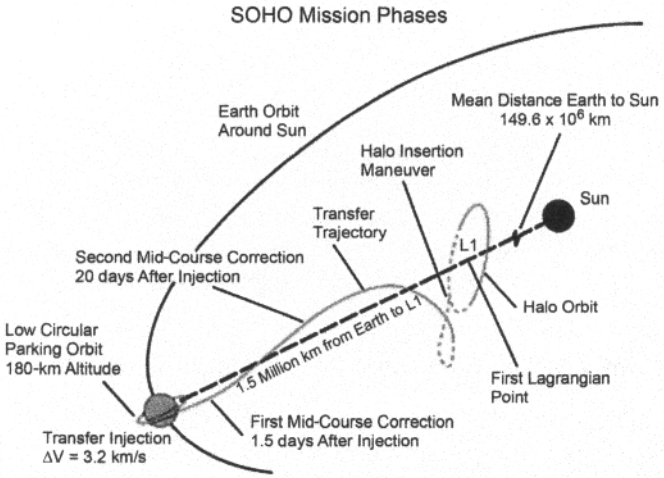

Figure 1-10 The transfer trajectories and mission phases of *SOHO* [68], used with permission of ESA.

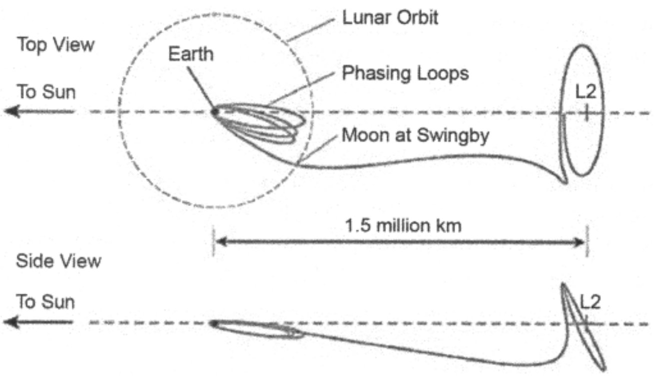

Figure 1-11 The transfer trajectory of *WMAP* [76].

Genesis. On August 8, 2001, *Genesis* launched and was quickly injected into a halo orbit about the Sun–Earth L_1 point. It traversed the halo orbit approximately five times, spending more than 2 years in the libration orbit collecting solar wind samples before turning back toward the Earth. Before returning to the Earth, however, it made a 3-million-mile (4.8×10^6 km) detour to visit the Sun–Earth L_2 point. The detour allowed it to deposit its science payload on the sunlit-side of the Earth. Figure 1-12 shows a plot of the trajectory that *Genesis* followed during its primary mission [71, 72].

Herschel and Planck. The Herschel and Planck space observatories were launched together on May 14, 2009 [73–75]. The two spacecraft separated soon after launch and traveled separately to Lissajous orbits about the Sun–Earth L_2 point. Their orbit transfers were heuristically similar to *WMAP*'s transfer to L_2, illustrated in Fig. 1-11.

Future Missions. There are plans to place the proposed James Webb Space Telescope [78] and the proposed Terrestrial Planet Finder [79] missions, among others, at the Sun–Earth L_2 point. Low-energy trajectories to the Sun–Earth Lagrange points have been shown to be very useful for solar observatories (L_1) and astrophysics observatories (L_2), and they frequently appear in spacecraft proposals.

1.6.3 Missions Implementing Low-Energy Lunar Transfers

Hiten/MUSES-A. In 1991, the Japanese spacecraft *Hiten* was the first spacecraft to transfer to the Moon using a low-energy lunar transfer. The spacecraft was not designed to go to the Moon, but rather to send a probe to the Moon. After the probe's communication system failed, mission designers scrambled to find a new mission for *Hiten*. Edward Belbruno and James Miller constructed a new trajectory—a "WSB transfer"—that required less fuel than traditional lunar transfers [80, 81]. The

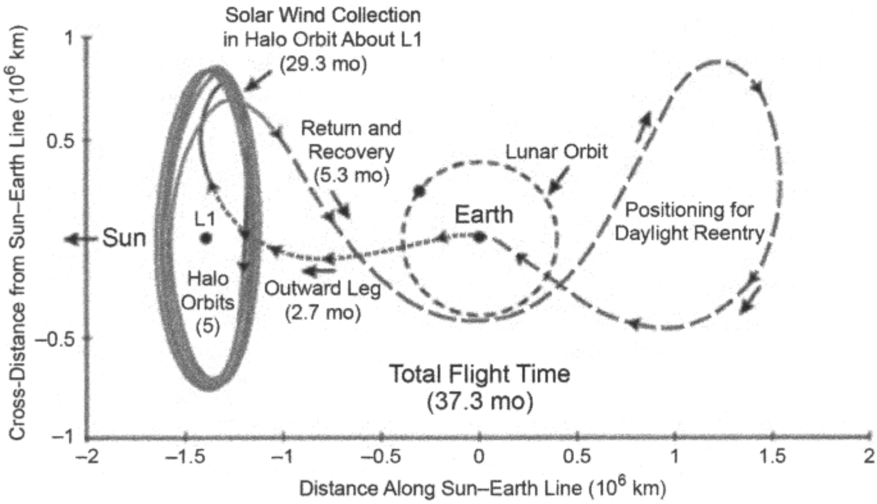

Figure 1-12 The low-energy trajectory that the *Genesis* spacecraft followed [77], viewed from above in the Sun–Earth rotating frame.

spacecraft *Hiten* did not have the fuel required for a conventional lunar transfer, but had the fuel to use this new lunar transfer to reach the Moon. *Hiten* became Japan's first lunar mission.

SMART-1. On September 27, 2003, the European Space Agency's *SMART-1* spacecraft followed a low-thrust 2-year trajectory to reach the Moon, becoming the first low-thrust spacecraft to transfer to the Moon [82].

ARTEMIS. The *Time History of Events and Macroscale Interactions during Substorms (THEMIS)* constellation was launched on February 17, 2007, to monitor the Earth's magnetic field from five different vantage points in high-altitude orbits, tracking the large-scale evolution of substorms. In 2009, two of those spacecraft were maneuvered to begin an extended mission called *ARTEMIS* [4]. The two spacecraft performed numerous maneuvers near their orbital perigees to gradually raise their orbits until they could take advantage of several lunar flybys to propel them onto two low-energy transfers. Both *ARTEMIS* spacecraft arrived at the Moon near the Earth–Moon L_2 point; one of them remained there and one immediately transferred to a libration orbit about the Earth–Moon L_1 point. After several months, the second spacecraft made the transfer and both orbited the L_1 point. After several more months, the two spacecraft departed their respective L_1 orbits, descended to the Moon, and entered smaller Keplerian orbits about the Moon. The two *ARTEMIS* spacecraft are the first two spacecraft to orbit either LL_1 or LL_2, and they each orbited both points.

GRAIL. The *GRAIL* mission (Fig. 1-13) [83–85] was launched on September 10, 2011, aboard a Delta II Heavy launch vehicle. Two vehicles, *GRAIL-A* (*Ebb*) and *GRAIL-B* (*Flow*), were separated soon after launch and flew independently to the Moon via two similar low-energy transfers. The two spacecraft arrived at the Moon approximately 25 hours apart, on December 31, 2011 and January 1, 2012. After a few months of orbit reductions and adjustments, the two spacecraft inserted into a formation, such that one spacecraft trailed the other in almost identical orbits about the Moon. By tracking each other, the two spacecraft were able to recover the Moon's gravity field to unprecedented precision and map the interior structure of the Moon. The two *GRAIL* spacecraft were the first ever to fly low-energy lunar transfers as part of their primary mission, and they were the first ever to arrive at the Moon and perform lunar orbit insertions directly from low-energy transfers.

GRAIL's trajectory design is illustrated in Fig. 1-13, including the first and last launch opportunity in a 26-day launch period. This is the launch period published in Ref. [83], however, it was actually extended by many days as the mission developed. As one can see in Fig. 1-13, *GRAIL*'s mission design includes two significant deterministic maneuvers executed per spacecraft during the cruise, performed primarily to separate their lunar orbit insertion dates.

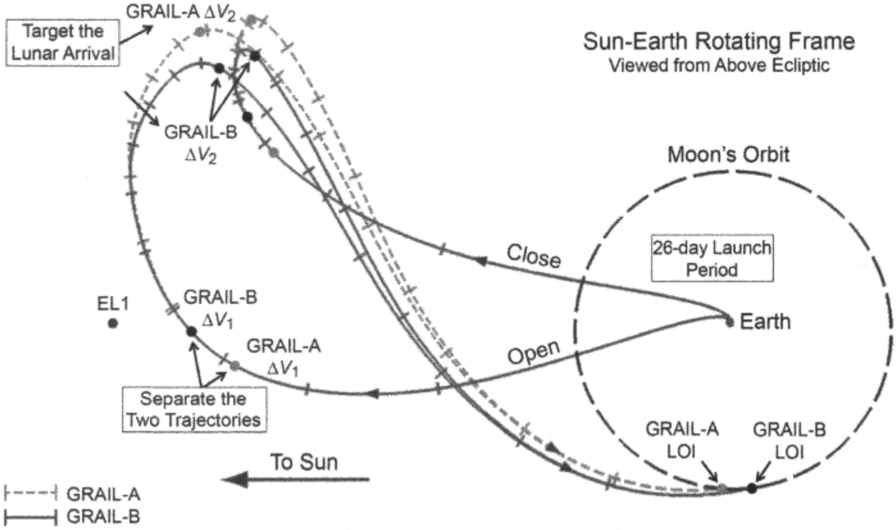

Figure 1-13 *GRAIL*'s mission design, including a 26-day launch period and two deterministic maneuvers for both *GRAIL*-A and *GRAIL*-B, designed to separate their lunar orbit insertion times by 25 hours (Ref. [83], originally published by AAS).

1.7 LOW-ENERGY LUNAR TRANSFERS

Low-energy transfers between the Earth and the Moon are the focus of this book; this section heuristically describes these transfers and how they are used.

A low-energy lunar transfer includes several segments and a wide variety of possible itineraries. The transfer may begin from a direct launch, a parking orbit, or some previous mission orbit. From the initial state, the spacecraft may depart immediately toward the low-energy transfer, or it may target an outbound lunar flyby. If the trajectory employs a lunar flyby, the mission may benefit by incorporating one or more Earth phasing orbits to target that flyby. The lunar transfer then spends 3–4 months before returning to the Moon. Upon arriving at the Moon, the spacecraft may immediately inject into a libration orbit or some other three-body orbit, a low lunar orbit, or it may immediately descend to the surface for a soft landing or a targeted impact. If the mission inserts into an orbit, it may later transfer to a different orbit and/or transfer to the surface. These itinerary choices and approximate performance parameters are illustrated in the flowchart shown in Fig. 1-14. This section describes each of these options in more detail.

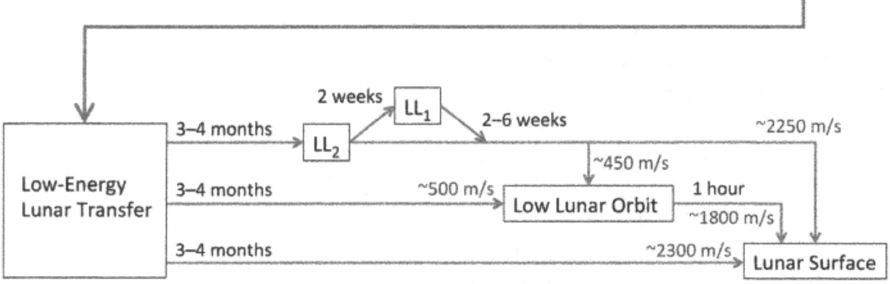

Figure 1-14 A flowchart illustrating different low-energy lunar transfer itineraries, with approximate C_3 values, transfer times, and ΔV values shown. For instance, a mission could use this flowchart to determine the approximate C_3 of taking a direct injection to a low-energy transfer (upper half), followed by the transfer duration and ΔV cost needed to transfer to a low lunar orbit (lower half). From there, one could transfer to the lunar surface, if desired (lower right).

Earth Parking Orbit. Low-energy lunar transfers may begin in any Earth parking orbit, including those compatible with a launch from any launch site around the world; they may also begin from nearly any preexisting mission orbit, which was the case for the *Hiten* and *ARTEMIS* missions [4, 81]. It is typically easier to tailor a mission to launch into a parking orbit and then depart that orbit onto a low-energy transfer than it is to adjust the orbit of a preexisting spacecraft to achieve a particular low-energy transfer. The surveys in this book assume that the mission begins in a 185-km circular low-Earth parking orbit, unless otherwise noted.

It will be shown that a given low-energy transfer has a natural Earth departure geometry—one that does not necessarily align with a desirable Earth parking orbit. Section 6.5 provides targeting procedures to connect a desirable Earth parking orbit, for example, one with an inclination of 28.5 deg, with a given low-energy transfer using 1–3 maneuvers and a minimal amount of fuel.

Trans-Lunar Injection. The trans-lunar injection (TLI) is modeled in this book as an impulsive ΔV tangent to the parking orbit. This maneuver is typically performed by the launch vehicle's upper stage. The launch vehicle's target C_3 value is typically in the range of –0.7 to –0.4 km^2/s^2, where C_3 is a parameter equal to twice the target specific energy. Since this target is negative, the resulting orbit is still captured by the Earth. If the trajectory is designed to implement a lunar gravity assist on the way out to the long cruise, then the launch target may be reduced to a C_3 of approximately –2 km^2/s^2. Launch vehicles typically target the right ascension and declination of the outbound asymptote for interplanetary missions to other planets. Since a low-energy lunar transfer is still captured by the Earth there is no outbound asymptote. The *GRAIL* targets included the right ascension and declination of the instantaneous apogee vector at the target interface time, referred to as RAV and DAV [83].

Trans-Lunar Cruise. A spacecraft's trans-lunar cruise on its low-energy lunar transfer takes it beyond the orbit of the Moon and typically in a direction toward either the second or fourth quadrant in the Sun–Earth synodic coordinate system [86]. The spacecraft typically ventures 1–2 million kilometers away from the Earth, where the Sun's gravity becomes very influential. As the spacecraft traverses its apogee the Sun's gravity constantly pulls on it, raising the spacecraft's perigee altitude. By the time the spacecraft begins to return to the Earth its perigee has risen high enough that it encounters the Moon. Further, the trajectory is designed to place the spacecraft on a lunar encounter trajectory. The *GRAIL* mission design involves two deterministic maneuvers and three statistical maneuvers for each spacecraft to navigate its trans-lunar cruise [84]. The transfers in this book may include up to two deterministic maneuvers performed during the trans-lunar cruise, and it is reasonable to assume that two or three statistical maneuvers are sufficient to implement a low-energy transfer unless a spacecraft has particularly challenging characteristics.

During this transfer, the spacecraft requires station-keeping to remain on its proper trajectory. The station-keeping cost is minimal and may be accounted for by trajectory correction maneuvers; the *Genesis* spacecraft followed a similar low-energy transfer and required only approximately 8.87 m/s of ΔV per year [71, 72, 87].

The low-energy transfer may include one or more Earth phasing orbits and/or one or more lunar flybys. These add complexity to the mission and may increase the number of maneuvers required to perform the mission, but may reduce the injection energy requirements or orbit insertion requirements upon arriving at the Moon.

Lunar Arrival. As the spacecraft approaches the Moon, it arrives on a trajectory that leads it to its initial lunar destination, be it a high-altitude three-body orbit, a low lunar orbit, or the surface of the Moon. If the spacecraft's destination is a three-body orbit, then the spacecraft often does not require any significant maneuver to enter the orbit (studied in Chapter 3); if the spacecraft's destination is a low lunar orbit, then the trajectory guides the spacecraft to its lunar orbit insertion state (studied in Chapter 4); finally, if the spacecraft's destination is the lunar surface, then the trajectory guides the spacecraft there at the designed flight path angle (studied in Chapter 5).