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An Architecture for Lunar Return Using Existing Assets

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Golden Spike Company

Abstract

The United States has a human space flight program that bypasses the lunar surface in favor of missions to Near Earth Objects and Mars. These are laudable goals, but the Moon also has much to offer. Limited budgets probably preclude a US government-sponsored human lunar exploration in the coming decade; however, the possibility exists for such to be accomplished by private enterprise. We posit that in order to bring costs within a range that might make a business case close, the mission must be relatively austere and make maximum use of existing assets and capabilities. This paper reports on a study conducted to evaluate the feasibility of lunar mission architectures primarily using as much existing or in-development, commercially available hardware and technology as possible. In particular, we study Dual Earth Orbit Rendezvous-Lunar Orbit Rendezvous (DEOR-LOR) and Dual Launch–Lunar Orbit Rendezvous (DL-LOR) missions using existing and in-development flight systems as examples. The solutions described here are found to be feasible, to substantially reduce development requirements relative to recent post-Apollo approaches involving entirely new launchers and crew capsules, and to offer the possibility of human lunar expeditions at costs not unlike robotic flagship exploration missions.

I. Introduction

Under the previous presidential administration, NASA initiated a program intended to return humans first to the Moon and later to venture on to Mars. This "Constellation" program involved development of two new large launch vehicles, Ares 1 and Ares 5, as well as new crew vehicles and landers. The present administration deemed this program unaffordable and cancelled it. After much political wrangling, a new compromise program has evolved incorporating incremental development of a new very large launch vehicle and a new crew vehicle capable of flight beyond low Earth orbit (LEO). This new program aims to accomplish missions to Near Earth Objects (NEOs) followed by missions to Mars. The lunar surface is no longer a target for NASA human exploration missions.

Another major thrust of the current space policy is to encourage private enterprise in space activities as manifested in contracts for private providers of cargo and crew transport to the ISS replacing the recently retired Space Shuttle.

All these factors motivated a study to investigate the feasibility of a Private Sector Lunar Return (PSLR) and to evaluate whether such a program might be the basis for a viable business, which will require both recurring and non-recurring costs to be held to a minimum. A corollary is to make maximum possible use of existing hardware and to develop only that which cannot be readily purchased. This is very different from the way government agencies typically approach such efforts, but it is instructive to recall that Columbus did not design and develop grandiose new ships for his explorations; he bought the best he could of existing hardware and made it work.

The PSLR study team involved the authors of this paper along with a number of other engineers, scientists, and business people interested in the concept. A set of viable mission scenarios for a first-return lunar expedition was developed and programmatic cost estimates were derived based upon the adopted mission concepts. Alternative approaches for critical areas were also developed. The results of that study are the basis for this paper.

The enterprise proposed here opens up the possibility for private individuals, private companies, space and science agencies abroad, or even US agencies to purchase transportation services to and from the lunar surface. Possible motivations might include individual ambition or curiosity, tourism, scientific investigation, or profit. Governments of other nations desiring to participate in space exploration but unable to afford a standalone lunar exploration program could, for example, purchase rides for scientists or other citizens for scientific and technical advancement or simply for national pride. Perhaps most importantly, this effort could extend the concept of commercial human spaceflight beyond LEO and into cislunar space and to the surface of the Moon itself.

A number of existing/in-development launch vehicles and human spacecraft in development could support such a program. Architectures that exploit the capabilities of these systems are described later in this report. The notable exceptions to this are a Lunar Lander, of which none now exist, and a capable new Crew Capsule Propulsion Module or stage. We have studied two workable concepts for lander development that are described herein.

II. Reasons to Return to the Moon

Human lunar missions have many purposes, but they may most broadly be broken down into four categories: scientific exploration, commercial activities, spaceflight operations, and personal motivations such as curiosity or prestige. We expand briefly on each of these below.

Scientific Exploration

The Moon is scientifically valuable both for the study of lunar origin and evolution, as well as for its place in comparative planetology, and the prospect of finding very old samples of the Earth believed to reside on the lunar surface as meteorites, akin to lunar meteorites found on Earth. The Moon has also been discussed as a potential site for astronomical observatories, and for certain applications for Earth observation sensors.

Commercial Activities

Numerous commercial lunar activities have been discussed in the past. These include resource mining, space tourism, fee-for-hire lunar scientific missions, and various entertainment-related products and services that gain value by virtue of being conducted on or near the Moon (both with and without people).

Spaceflight Operations

The Moon, by dint of its proximity to Earth and its relatively shallow gravity well, provides opportunities to gain experience in living in and operating space systems before moving on to farther and more difficult locales in the solar system. Further, lunar polar resources, most notably water, may someday be exploited to refuel interplanetary and cislunar spacecraft without the need to return them at higher cost into Earth's deep gravity well.

Curiosity and Prestige

Lunar missions are more difficult than Earth orbital missions, and offer new experiences and challenges. Therefore, nations, corporations, and individuals leading or participating in lunar expeditions will gain prestige and achieve their personal goals.

A simple, easy to develop, less expensive lunar exploration architecture can be used to advance any or all of these kinds of objectives.

III. Existing Assets

Launch vehicle candidates identified for our original study include the already-flying United Launch Alliance (ULA) Atlas V, ULA Delta 4, and Space Exploration Technologies, Inc. (SpaceX) Falcon 9 series of launch vehicles. Subsequently the development of the Falcon Heavy was announced. While this privately developed heavy lift launcher has not yet flown, its potential is so great that the original study was extended to include it.

As a potential crew capsule for Earth to lunar orbit transportation, we considered the Space X Dragon. This capsule has flown successfully to LEO and back twice, and was designed to be capable of lunar return velocity. Other capsules under development, such as Boeing CST-100, and Liberty, might also be candidates but we have not evaluated their suitability here. In addition, our study included notional 1-person and 2-person lunar landers after preliminary scoping analysis. No foreign launchers or crew transports were evaluated in this study.

Necessary modifications to the Falcon 9, Atlas V, Falcon Heavy and Dragon to accomplish the lunar exploration missions we describe will be discussed below.

Atlas V

(Courtesy ULA)

Figure 1

Falcon 9

(Courtesy SpaceX)

Figure 2

Note that the architectures described herein are intended to demonstrate the feasibility of the proposed lunar missions. Other architectures and vehicle combinations are possible, especially as new stages come on line, but were not studied here.

Atlas V

The Atlas V series of launch vehicles (Fig 1), produced by ULA, consists of several vehicles of varying capability depending upon the number of solid propellant strap-on motors and the number of engines in the second stage. The first-stage core vehicle burns RP-1 (kerosene) and liquid oxygen; the second stage, Centaur, burns liquid hydrogen and liquid oxygen. The Atlas V 500 family is of particular interest for use in the Golden Spike program. The Atlas V 55x family is the most powerful of these, using 5 solid propellant rocket motors augmenting the first stage. Either the 551 version (one RL-10 engine in the second stage) or the 552 (two RL-10s) are possibilities. The 552 has less gravity loss in the second stage due to higher thrust but is heavier. The 552 seems better for our application but more detailed analysis might change this conclusion. Atlas V has an excellent reliability record with nearly 30 consecutive successful launches of all its variants.

The Atlas V 552 can deliver 20,520 kg (45,239 lbm) into a 185 km (100 nmi) altitude circular LEO at 28.5 degree inclination when launched from Cape Canaveral, Florida (Ref 1). The vehicle is not presently man-rated, however ULA is currently pursuing such qualification in collaboration with NASA.

Falcon 9

The Falcon 9 launch vehicle (Fig 2) is a recently developed medium lift vehicle developed by SpaceX. At this writing it has made four launches, all successfully reaching orbit, with the third and fourth both demonstrating ISS resupply capability. Over 40 launches are now under contract through 2017. The Falcon 9 is capable of lifting 16,700 kg (36,740 lbm) to 200km (108 nmi) LEO. This vehicle employs two stages and burns RP-1 and LOX propellants in both stages. Nine Merlin engines are used to power the first stage, and a single Merlin-vacuum engine powers the second stage.

The Falcon 9 was designed from inception to be capable of carrying crew, with all requisite factors of safety and redundancy intended to meet crew safety and reliability requirements. SpaceX is currently developing an associated crew escape system. The Falcon 9 is the booster used to launch SpaceX's Dragon cargo and crew spacecraft into orbit for NASA under a contract to resupply the ISS.

Table 1 presents LEO payload capability for Atlas V 552 and Falcon 9.

Table 1

Atlas V 552 and Falcon 9 – 180 to 200 km LEO Payload

Atlas 552	Falcon
20,520 kg 45,239 lbm	16,700 kg 36,740 lbm

Falcon Heavy

Falcon Heavy makes use of the existing Falcon 9 first and second stages. Three uprated Falcon 9 first stages are joined in a parallel configuration (Figure 3). All three ignite for liftoff. The second stage is essentially the same as the Falcon 9 second stage. The forecast payload capability of this vehicle is the largest available since last flight of NASA's Saturn V in 1973. Table 2 presents the payload capability of Falcon Heavy to LEO and to higher orbits.

Because Falcon Heavy has not yet flown, and in recognition of the realities of launch vehicle development, our analysis discounts its performance values for lunar missions by 10%.

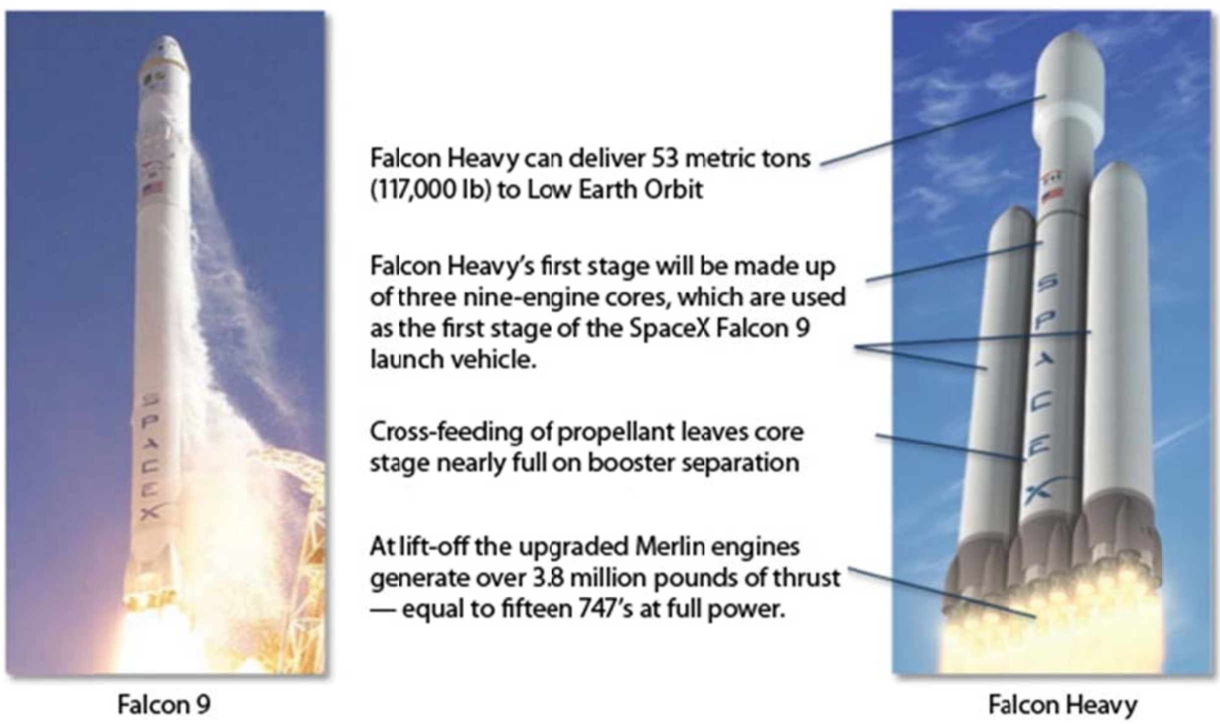


Figure 3

Falcon Heavy (Courtesy Space X)

Table 2

Falcon Heavy Payload Performance

	Low Earth Orbit (LEO)	Geostationary Transfer Orbit (GTO)	Lunar Transfer Orbit (LTO)
Published Performance	53,000 kg 116,600 lbm	20,000 kg 44,000 lbm	9700 kg 21,340 lbm
Discounted Performance	47,700 kg 105,000 lbm	18,000 kg 39,600 lbm	8730 kg 19,200 lbm

Two possible scenarios exist for use of the Falcon Heavy in a lunar exploration architecture.

The first, and most desirable from a performance viewpoint, is to integrate an upper stage equivalent to the Centaur III used on Atlas V onto the Falcon Heavy. Falcon Heavy has ample LEO capability to place the fully loaded Centaur III equivalent, with a Lunar Dragon and propulsion module, into orbit. Two sub-options then arise. In one sub-option, the upper stage expends all of its propellant to place a Lunar Dragon with an 1800 m/sec propulsion module into LTO and is then jettisoned. The Dragon propulsion module then proceeds to the Moon where the propulsion module expends 900 m/sec of its capability to enter low lunar orbit (LLO). The other sub-option is that the Centaur equivalent is modified to retain propellant for a sufficient time to reach the Moon; ULA has extensively studied such modifications to the Centaur. In this option, the Centaur equivalent stage delivers the Dragon with a lighter 900 m/sec propulsion module into LLO and is then jettisoned. Table 3 presents estimated payload for the Falcon Heavy/Centaur III equivalent combination.

Table 3

Falcon Heavy/Centaur III Equivalent Stage

Payload to LTO and LLO

Destination Orbit	Payload (kg/lbm)
LTO	23169 / 50971
LLO	17423 / 38330

Another option is to develop a stand-alone propulsion module for the Dragon. The Falcon Heavy alone can deliver the mass of the Dragon plus a 2400 m/sec propulsion module into an orbit energetically equivalent to a geostationary transfer orbit (GTO), but optimized for transfer to the Moon. The Dragon propulsion module[1] then increases Dragon's velocity by 600 m/sec to place the assembly on a LTO. From that point the mission proceeds as in the first option above.

Dragon

For purposes of this study, we have used the SpaceX Dragon spacecraft as a baseline, although there are additional candidates at various development stages, including the Boeing CST-100

[1] Note that none of the ΔV values we assume for the Dragon/propulsion module combination take account of the ΔV capability of the Dragon itself. This capability provides for mid-course corrections and provides some contingency against underperformance or other issues.

and Liberty. The Dragon can carry as many as 7 persons (primarily for ISS support) and has a life support system with 35 person-days capability. The re-entry thermal protection system is designed for lunar return conditions. The Dragon also has a rear structure called the Trunk which serves as a cargo module for ISS supply missions, which adapts the Dragon capsule to the launch vehicle.

Dragon's on-board propulsion can provide up to 400 m/sec ΔV for the basic Dragon[2]. The ΔV capability of the onboard Dragon propulsion is of course reduced due to the increased weight of Lunar Dragon over that of the basic Dragon, but it is still ample for trajectory correction and minor orbit adjustment

To enter and depart lunar orbit, additional Dragon propulsion is required, but this propulsion system can be located within a modified Trunk structure, as discussed in more detail below.

The Dragon can remain in lunar orbit for up to 7 days to support a landing or carry out other tasks, such as a dedicated orbital science mission. In the case of a landing mission, the Dragon would rendezvous and dock with the lander previously delivered. The lander would then proceed with its mission and return to dock with the Dragon. Dragon would expend the remainder of its propulsion module ΔV to return to Earth leaving the ascent stage of the lander in LLO until the orbit naturally decays over a period of weeks to months.

Table 4 presents masses for the various Dragon plus propulsion module options. These propulsion masses are based upon a LO_2/LH_2 propulsion system using Pratt & Whitney's Rocketdyne (PWR) RL-10 engine, which is designed to allow long-term storage in space.

[2] Might be less, depending upon the amount of short pulse firings versus longer burns.

Table 4

Mass of Dragon With Propulsion Module

Case	Dragon & Trunk Mass* (kg) (lbm)	Propulsion Dry Mass (kg) (lbm)	Propellant Mass (kg) (lbm)	Initial Mass (kg) (lbm)
LLO to ETO (cryo) (900 m/sec)	8853 19,477	445 979	2172 4779	11,470 25,235
LTO/LLO /ETO (cryo) (1800 m/sec)	8853 19,477	850 1871	5068 11,149	14,771 32,497
GTO/LTO/LLO/ETO (cryo) (2400 m/sec)	8853 19,477	1196 2631	7534 16,575	17583 38683
LLO to ETO (storable) (900 m/sec)	8853 19,477	541 1190	3119 6862	12513 27528

*Includes crew of 2 @400 lbm and 250 lbm cargo. Masses adjusted for 8 days boiloff

The extended Dragon Trunk provides ample volume for the RL-10 engine and even the largest required propellant volume, leaving ample room for pressurant tanks and associated hardware.

The lowest ΔV option for the Propulsion Module, 900 m/sec, allows a storable propellant option based upon the Delta II upper stage engine. Mass information is presented in Table 4 above. Because of the high density of the propellant this system will fit in a standard length Dragon Trunk. The major advantage of this option is a significant loosening of time constraints by eliminating propellant boiloff as an issue. However, it does mandate the mission mode in which the Centaur delivers the Dragon assembly to LLO, since the propulsion module only provides enough Delta V to depart LLO for ETO.

IV. Planning and Operations

In addition to existing vehicles, tools for mission planning, onboard operations activities, and ground support are readily available. Today, these functions can be accomplished without a complex computer facility or large, Apollo-style mission control rooms.

Planning Tools

Large computer systems with multiple hand-tailored programs were required in the Apollo era to plan missions, to develop the exact trajectory profile, and to generate onboard guidance and targeting parameters. In 1969, to generate a single transearth injection solution (from lunar orbit) required several minutes of compute time on an IBM 360 computer. Today, these functions can be performed with commercial-off-the-shelf software on a desktop computer in a few seconds. For example, the Satellite Tool Kit from Analytical Graphics, Inc. has supported NASA's Lunar Crater Observation and Sensing Satellite (LCROSS), the Wilkinson Microwave Anisotropy Probe (WMAP), and the Lunar Reconnaissance Orbiter (LRO) missions in their lunar phases. Algorithms for trajectory, navigation, and guidance processors are all mature and available. In addition, enhanced control laws used to compute the descent engine thrust level for a lunar landing are available to optimize propellant usage. The Kinetic Controller (formulated by Charles Deiterich) and the Fuzzy Logic control (defined by Lotfi Zadeh) represent examples of such advances [Ref 2].

Onboard Operations

Advances in flight avionics and onboard software have progressed to the point where onboard autonomous mission control is practiced on many space missions. Precision inertial navigation and guidance systems with integrated GPS are currently available from Honeywell International Inc. For LEO activities, GPS capabilities have eliminated the requirement for continuous ground radar tracking. And a decade ago, the AMSAT AO-40 satellite was the first to demonstrate autonomous tracking of GPS signals from within a High Earth Orbit (1,042 km x 58,691 km) with no interaction from ground controllers [Ref 3]. Automatic star tracker systems are available to maintain the guidance system inertial platform alignment. Lunar and cislunar navigation can be achieved with automated optical tracking systems. Recent studies comparing the Apollo program optical navigation system and subsequent technology advances have shown the viability for automated onboard cislunar navigation for the Orion program [Ref 4]. Ball Aerospace has a long history of excellence in the field of star trackers and optical systems.

Current onboard computer, networking, and sensor technologies will provide automated monitoring and control of vehicle systems to ensure proper functioning and to manage systems redundancy. To aid in vehicle performance analyses and contingency support, the health and operations of the onboard systems will be available to the ground team via telemetry. For example, Southwest Research Institute and Aeroflex Inc. can both supply commercial-off-the-shelf telemetry and sensor systems.

Ground Support

Although the flight vehicles will be able to complete lunar missions largely unaided, the ground team will always be available to support the flight crew. Engineering evaluations, procedures development, and crew training will be accomplished on common simulation hardware. While training and mission preparation will help the flight crew deal with and understand most possible in-flight contingencies, the ground team will be ready to support unanticipated situations. Ground based radar navigation, when required, is currently available on contract and eliminates the need for in-house tracking capability. The Universal Space Network, Inc. (USN) has the largest ground-based network in the world, and has supported multiple space activities for governmental space agencies, private technology firms, and educational institutions. Via whatever ground-based network is selected, the ground team will have access to down-linked spacecraft data to evaluate the health of the in-flight systems, develop alternate mission plans as required, and provide general flight information and progress reports.

V. Derived PSLR Mission Architecture

Lunar Flyby and Lunar Orbit Missions

All missions described in this paper assume a crew of two persons. The Dragon’s current life support system provides up to 35 person-days of support. Assuming three-day trajectories to and from the Moon, and allowing a few days of margin, the system easily accomplishes a lunar flyby, and permits at least a week-long capability in lunar orbit for a crew of two.

Our flyby and orbital lunar mission architecture is based around a trajectory to the Moon, as first demonstrated by Soviet Zond vehicles in the late 1960s and used by early Apollo missions. Our architecture requires two launches and an Earth Orbit Rendezvous (EOR). The first launch places a Centaur Lunar Transfer Vehicle (LTV) launched aboard an Atlas V into LEO. The Centaur then re-tanks from the drop tank, which it carried into orbit. A lunar-capable Dragon spacecraft, with crew, is then launched into a rendezvous orbit using a Falcon 9 or one of the smaller-capacity Atlas series launchers. Upon achieving rendezvous with the reloaded Centaur, the Dragon docks with the Centaur. After system verification, the Centaur fires its engines and places the Dragon in a free return Lunar Transfer Orbit (LTO). After about three days, Dragon flies by the Moon at low altitude. The Moon's gravity redirects the trajectory back toward the Earth where, after another approximately 3 days, Dragon re-enters the Earth's atmosphere for landing. Dragon's existing onboard propulsion system is ample for all required trajectory and orbit adjustments on a lunar flyby. This is the minimum cost and complexity lunar mission, since it involves no additional propulsion module for Dragon but uses Dragon in its basic form. It could therefore be the first mission flown while the Dragon lunar propulsion module is still in development.

A more complex mission profile, referred to as the "Apollo 8" mode, accomplishes lunar orbital missions. Two options have been identified for this mission architecture.

One possibility is to use the refueled Centaur approach described above. The Centaur LTV places a Dragon with a 900 m/sec propulsion module in LTO. Upon arrival at the Moon the propulsion module applies a 450 m/sec ΔV to the spacecraft inserting into an elliptical lunar orbit with closest approach (periselene) at about 60 km above the far side, and an aposelene of about 5700 km. Figure 4 shows the orbit. After a few days in lunar orbit, the propulsion module fires again to place Dragon in an Earth transfer orbit (ETO) for an entry and landing as described above.

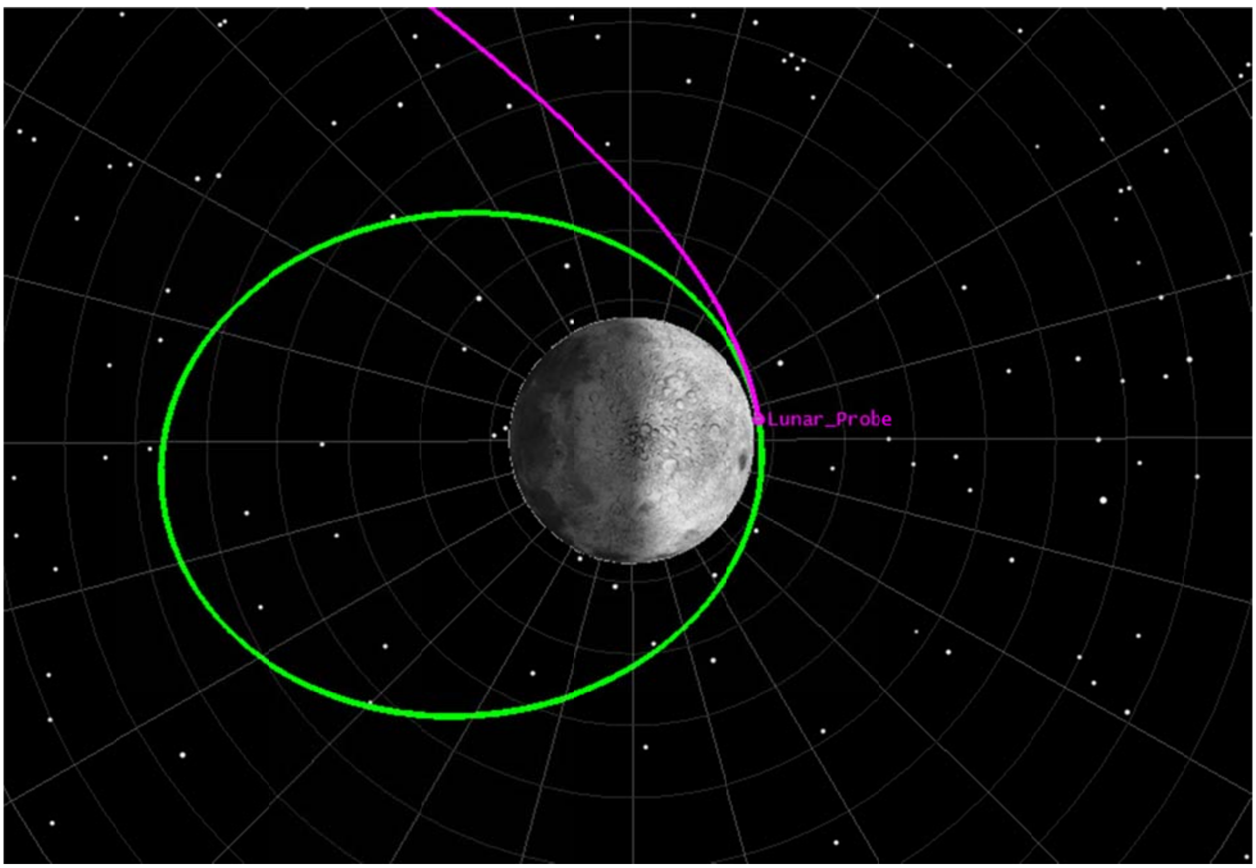


Figure 4

The Elliptical Lunar Orbit Described Here

The second approach is to launch a fully lunar-capable Dragon as described previously using a Falcon Heavy launcher with a Centaur-equivalent upper stage. For this reference mission the orbit would be circular at 60 km. Dragon's existing onboard propulsion system provides significant orbit altitude adjustment capability.

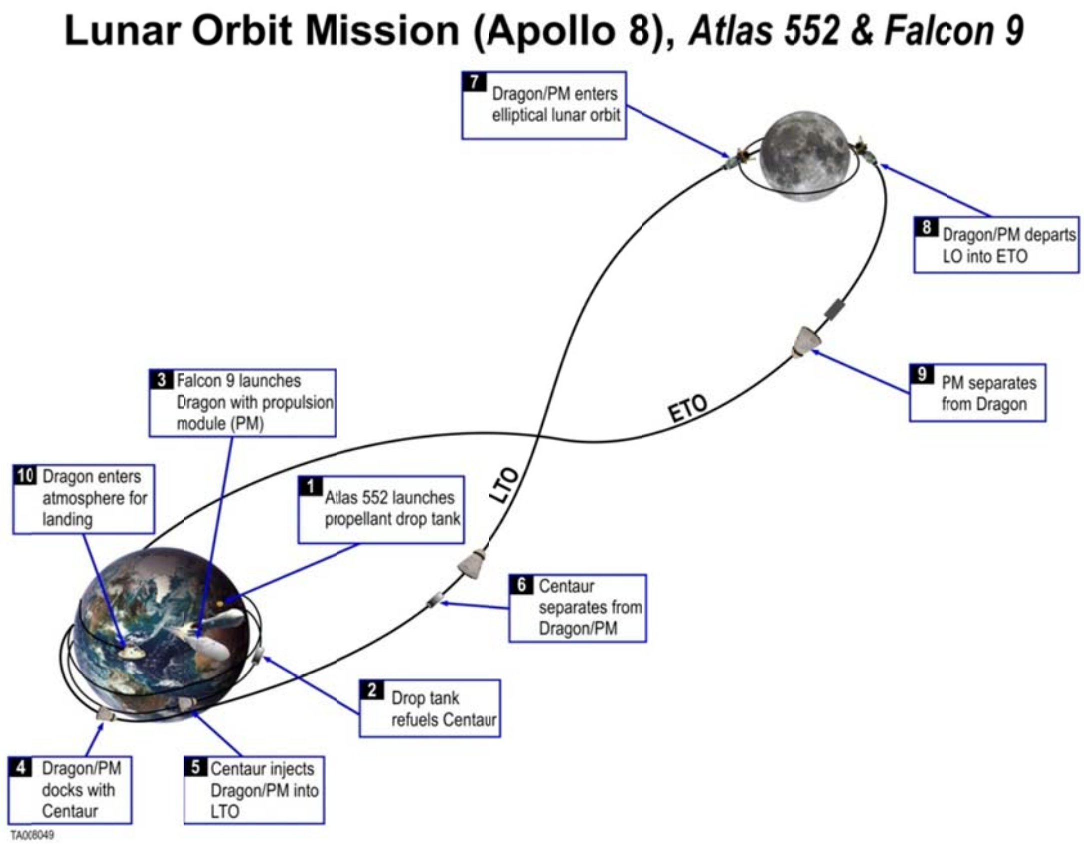
The lunar flyby and lunar orbit missions described here have the programmatic advantage that they can occur before development of the lander vehicle is complete, or even begun, thus substantially reducing early program costs while offering an early lunar orbit capability for substantially lower cost than landing expeditions.

Lunar Landing Missions

We now consider lunar landing missions. We concentrate here on a landing mission architecture based on use of the Falcon Heavy launcher now in development; other launch scenarios involving Atlas Vs and Falcon 9 pairs, as discussed above, have also been studied but are not discussed here.

Use of the Falcon Heavy also represents a logistical simplification, as it makes the landing mission a two-launch effort. In this architecture, the first Falcon Heavy launches to LEO a fully loaded Centaur-equivalent stage and a lander as payload. The Centaur upper stage then launches the lander onto a trans-lunar coast and delivers the lander to LLO where it waits for the crew vehicle to arrive. The Dragon, with crew, and equipped with a 900 m/sec propulsion module, is then delivered to LLO by a second Falcon Heavy/Centaur-equivalent launch. The Dragon and Lander then rendezvous and dock in LLO. The crew leaves Dragon, enters the lander, and lands on the Moon. When surface activity is concluded the crew ascends to LLO aboard the lander, which next achieves rendezvous and docking with the Dragon. The crew enters Dragon and, at a suitable time, fires the propulsion unit to return to Earth.

We have also investigated use of the Falcon Heavy with purpose-built smaller stages, rather than Centaur or its equivalent. This option would make use of the significant payload delivery capability of the Falcon Heavy to the energetic equivalent of Geostationary Transfer Orbit. This mission architecture requires development of a propulsion unit capable of imparting a 2400 m/sec ΔV to the Dragon to perform trans-lunar injection, lunar orbit insertion, and trans-Earth injection, as discussed above. The same propulsion module could be used to deliver the lunar lander to LLO on a separate Falcon Heavy launch.



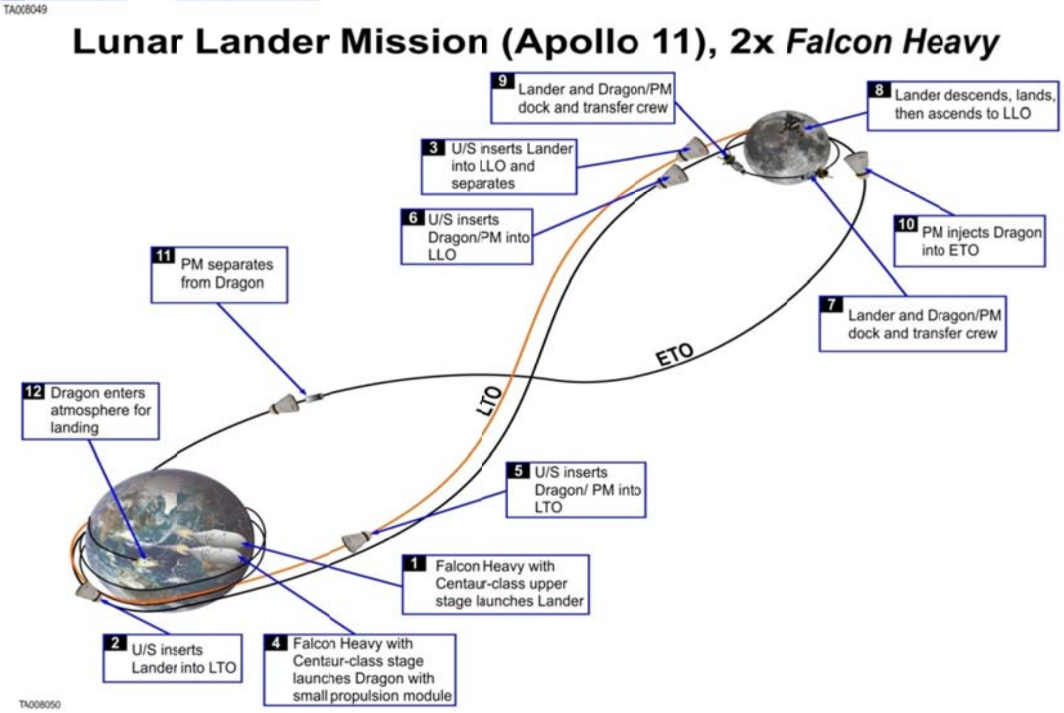


Figure 5

Mission Architectures

VI. Required New Elements

Falcon Heavy Centaur Equivalent

While not a new technology development *per se*, the placement of the Centaur onto a launch vehicle requires significant integration, though certainly much less than the development of a new vehicle like Ares would have required. A recent successful example of such an integration occurred when a Boeing STAR-48 stage was integrated onto an Atlas V 551 for use by NASA's New Horizons mission.

Propellant Drop Tank Required for Atlas V Mission Scenarios

In order to propel the lunar lander or the basic Dragon crew capsule to lunar orbit using the Atlas V (as discussed), it is necessary to reload the nearly depleted Centaur upper stage with propellant after injection into LEO. In order to accomplish this, the Atlas V upper stage carries into LEO a payload consisting of an insulated tank loaded with 18,000 kg (39,600 lbm) of propellants. Of this quantity, 17,000 kg (37,400 lbm) is transferred into the nearly empty Centaur tanks, the 1000kg (2200 lbm) difference being that lost to boiloff during the transfer and chill-down processes. The amount transferred to the Centaur amounts to about 80% of a full propellant load for Centaur III. Figure 6 shows the configuration and details required modifications to the Centaur.

The reloaded Centaur LTV can deliver over 13,000 kg (28,600 lbm) to LTO and 8100 kg (17,820 lbm) from LEO to LLO (see Fig 6).

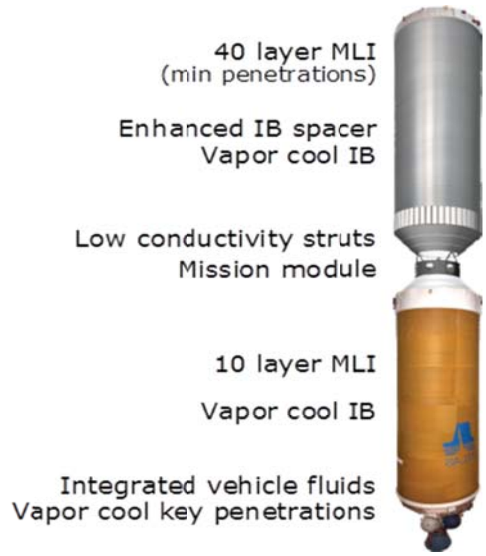


Figure 6

Propellant Drop Tank (Courtesy ULA)

The information presented above, including mass numbers, results from in-house studies by ULA of the Centaur as an Earth departure stage for deep space missions. ULA's extensive experience operating the Centaur in orbit, managing cryogenic propellant for multiple starts, and operating for extended periods gives confidence that this function can be carried out reliably. It will be necessary to demonstrate and qualify this propellant transfer function in orbit. NASA and ULA are already taking steps toward this end.

Dragon Lunar Propulsion Module

As described above, in order for the Dragon to perform the various missions discussed here, additional propulsion capability above that of the baseline Dragon is required. Depending upon the mission architecture selected, the ΔV capability of the propulsion module can range from 900 m/sec to 2400 m/sec. The lower end of this range is sufficiently small that it can be supplied by either a storable propellant system or a cryogenic propellant system. The higher ΔV requirements favor cryogenic systems.

Lunar Lander

Since the termination of the Apollo program, no crewed lunar landing vehicle has existed. Our study determined that a smaller, lighter vehicle using current technology would be preferable to a recreation of the Apollo lander, for both technical and cost reasons. Two lander variants were characterized in our feasibility study, one set using cryogenic propellants and another using storable propellants. For performance requirements, the analysis used published values for required ascent and descent profiles flown by the Apollo Lunar Module. These values were increased by 125 m/sec for both ascent and descent to allow for use of a "frozen orbit" consistent with our lander having to loiter in LLO for some weeks to months awaiting crew arrival. This orbit is designed to precess so that the orbiting spacecraft passes over the landing site on each orbit to ensure the option of return and rendezvous on every orbit. The ΔV requirements thus computed are 2625 m/sec (8610 ft/sec) for descent and 2345 m/sec (7692 ft/sec) for ascent.

In order to establish the minimum mass for a lunar lander, one and two-person unpressurized landers were evaluated at a conceptual design level. For a one-person unpressurized lander, a payload mass of 620 kg (1365 lbm) was used and for a two-person unpressurized lander a payload mass of 1000 kg (2200 lbm) was used. These numbers include allowances for crew, life support (including suits), avionics, control, and structure, and are based upon in-house studies conducted by Paragon Space Development Corp. A 30% mass margin was then added to the computed values.

In order to establish minimum mass case on the lander, the landers studied above did not include a pressurized habitat. While the redundancy of a pressure vessel appears to increase safety, similar values for probability of crew loss can be obtained by means such as inflatable emergency habitats, increased consumable supplies, and suit design. Although a lander without a habitat limits lunar surface stay time, it may be an acceptable compromise for some kinds of initial lunar surface missions.

However, a two-person lander with a small, pressurized cabin that allows a longer stay on the surface was also evaluated. This cabin would be similar in dimension to the cabin of a two-seat automobile or small airplane, and not unlike a Gemini capsule. A double wall, each capable of independently withstanding the pressure load of 5 psia with 3:1 safety factor provides redundant protection. There is no airlock. If the entire structure were made of mylar, the estimated mass increase is to accommodate the pressure load is 41 kg (90 lbm); for aluminum the penalty would be 73 kg (160 lbm). A 30% contingency is included in both cases. For conservatism, the heavier mass was used for the summary tables below but for this application the lighter plastic structure may be acceptable.

As noted above, we studied two lander propulsion variants. The cryogenic propulsion option (studied by original study team member Jeffrey Greason and modified by lead author James R. French for payload consistency) considered two possibilities for propellants: liquid oxygen/liquid hydrogen and liquid oxygen/liquid methane. While the engines were not specifically detailed, the PWR RL-10 was taken as the model. The oxygen hydrogen version was assumed to deliver 445 seconds I_{sp} while the methane version is assumed to deliver 355 seconds I_{sp}. (Operation of the RL-10 using methane was demonstrated a number of years ago and the throttling capability has been demonstrated as well.)

Our goal here was to develop a conceptual single-stage liquid fueled reusable Lander/ascent vehicle in the hope that, as the system matures, an advanced version of the lander could be resupplied with propellant in low lunar orbit and reused for several missions, reducing per-mission recurring cost. One of the major concerns of both cryogenic options, but particularly the LH_2 fueled concept, is the time in LLO awaiting the arrival of the crew. Minimization of propellant boiloff will be essential. This may be the major argument in favor of the LCH_4 concept and still more so for the fully storable concepts discussed below. More study is required.

The propellant combination used in the fully storable lander studies (conducted by lead author James French) was constrained to use earth-storable propellants (for operational simplicity) and to use existing propulsion hardware that could be adapted with minimum development. After looking at a variety of options, the concepts which produced a viable result were two-stage vehicles using a lander stage and an ascent stage. Each stage used a solid propellant rocket motor supplemented by liquid propellant rocket engines now available.

Table 5

Characteristics of Cryogenic Propellant Landers Studied Here

Crew	Single StagePropellants	Initial Mass in LLO (kg)/(lbm)	Mass on Lunar Surface (kg)/(lbm)	Mass at Lunar Liftoff (kg)/(lbm)	Mass to LLO (kg)/(lbm)
2 Unpressurized	LO_2/LCH_4	9041/19890	4306/9474	4306/9474	2220/4884
2 Unpressurized	LO_2/LH_2	5947/13083	2833/6232	2833/6232	1460/3213
2 Pressurized	LO_2/LCH_4	9674/21282	4607/10137	4607/10137	2375/5226
2 Pressurized	LO_2/LH_2	6363/13999	3031/6669	3031/6669	1562/3437

This approach eliminates the future reusability option mentioned above, but will be significantly less expensive to develop than the reusable cryogenic vehicle.

The following tables 6 thru 8 provide the performance values used in the study (Ref 6 & 7).

Table 6

Existing Qualified and Flown Storable-Propellant Engines

Hardware	Propellants	I_{sp} (sec)	Weight (kg)/(lbm)	Thrust (n)/(lbf)	Throttle
R-40B	NTO/MMH	293*	6.8/15	3960/900	3:1
R-42	NTO/MMH	303*	4.55/10	880/200	3:1

*These engines were used together in various combinations so a conservative average I_{sp} of 295 sec was used in the initial analyses. We recognize that these engines are not designed to throttle; however, they are designed to run in blowdown mode through the pressure range implied above. Installation of throttling valves in the propellant feed lines would allow them to function as throttling engines.

Table 7

Existing Qualified and Flown Solid Propellant Motors

Hardware	Propellants	I_{sp} Effective (sec)	Weight at Ignition (kg)/(lbm)	Weight at Burnout (kg)/(lbm)	Thrust (avg) (kn)/(lbf)
STAR 48A	TP-H-3340	289.9	2587/5691	134/294	78.1/17,750
STAR 48B	TP-H-3340	292.1	2146/4721	117/258	67.9/15,430
STAR 37VG	TP-H-3340	293.5	10872391	104/229*	56.3/12,800

*Includes weight for thrust vectoring nozzle. Other two fixed nozzle.

Table 8

Tested But Not Yet Qualified or Flown Improvements of Above Liquids Systems

Hardware	Propellants	I_{sp} (sec)	Weight (kg)/(lbm)	Thrust (n)/(lbf)	Throttle*
R-40B1	NTO/MMH	297	6.82/15	3960/900	3:1
R-42DM	NTO/hydrazine	327	4.55/10	880/200	2.5:1

*We recognize that these engines are not designed to throttle; however, they are designed to run in blowdown mode through the pressure range implied above. Installation of throttling valves in the propellant feed lines would allow them to function as throttling engines.

The highly reliable STAR 48A solid propellant rocket motor was applied in the descent stage and the STAR 37VG in the ascent stage. The liquid engine provided thrust vector control for the STAR 48 and then continued as primary propulsion after burnout and jettison of the solid. A similar scheme was used for ascent stage except that the STAR 37VG has a gimbaled nozzle obviating the need for the liquids to provide any control (except in roll) during the ascent solid burn. The results of the design study are presented in Table 9, showing use of hardware that has been qualified and flown, and Table 10, showing the results using demonstrated but not yet flight qualified (at the time of the study) improvements to the engines in Table 9.

Table 9

Characteristics of the Storable Propellant Lander

(Using currently qualified engines)

Crew	Descent Stage	Ascent Stage	Initial Mass in LLO (kg)/(lbm)	Mass on Lunar Surface (kg)/(lbm)	Mass at Lunar Liftoff (kg)/(lbm)	Mass to LLO (kg)/(lbm)
1 Unpressurized	STAR 48A + liquid	All liquid	8755/19262	3420/7524	2545/5599	1132/2490
1 Unpressurized	STAR 48A + liquid	STAR 37VG + liquid	7602/16725	2951/6493	2229/4903	898/1975
2 Unpressurized	STAR 48A + liquid	STAR 37VG + liquid ascent	11390/25057	4498/9896	3294/7246	1402/3085
2 Pressurized	STAR 48A + liquid	STAR 37VG + liquid ascent	12150/26731	4811/10584	3523/7750	1504/3309

Table 10

Characteristics of the Storable Propellant Lander

(Using Improved engines)

Crew	Descent Stage	Ascent Stage	Initial Mass in LLO (kg)/(lbm)	Mass on Lunar Surface (kg)/(lbm)	Mass at Liftoff (kg)/(lbm)	Mass to LLO (kg)/(lbm)
1 Unpressurized	STAR 48A + liquid for lander	All liquid ascent	7712/16967	3013/6628	2285/5028	1095/2410
1 Unpressurized	STAR 48A + liquid for lander	STAR 37VG + liquid ascent	7540/16589	2911/6405	2193/4825	893/1965
2 Unpressurized	STAR 48A + liquid for lander	STAR 37VG + liquid ascent	10598/23315	4194/9227	3112/6847	1373/3023
2 Pressurized	STAR 48A + liquid for lander	STAR 37VG + liquid ascent	11343/24954	4500/9901	3328/7321	1477/3250

Note that the reduced performance of the propulsion systems used here as compared to the cryogenic systems discussed above requires reduction of the crew size to one for some mission profiles. Further, use of the high mass-fraction solid motor in the ascent stage makes a significant improvement in the case of the lower performing liquids but becomes much less significant with the improved liquid motors. Further improvements for the subject liquid propellant systems have been investigated but would be costly to develop and qualify.

Table 11 below briefly summarizes the pros and cons of the cryogenic and storable approaches, and Fig 7 below provides an artist's conception of a pressurized lander.

Table 11

Pros and Cons of the Lander Concepts Evaluated

Lander Variant	**Pros**	**Cons**
Cryo	Two crew (using LH_2) Higher mass margin	More complex/costly development Propellant storage issues on-orbit
Conventional	Straightforward development Good on-orbit propellant storability	Single-crew in some options Lower mass margin

Figure 7

Artist Concepts of a Notional Pressurized Lunar Lander

A variety of options exist for delivering the lunar lander to LLO. The Atlas V-launched Centaur, with propellant replenished from a drop tank carried into LEO can deliver to LLO the single stage LO_2/LH_2 lander with ample margin. The LO_2/LCH_4 lander is too large as a two-person vehicle to reach LLO but would have substantial margin as a one-person vehicle on the reloaded Centaur.

The largest Dragon Propulsion Module we studied (2400 m/sec) operating for example from a Falcon Heavy from a GTO-equivalent orbit, is another candidate to deliver the lander to LLO. In this mission, the module need only provide 1500 m/sec (4940 ft/sec) so that its maximum payload is 11,561 kg (25,434 lbm). Thus it can deliver all lander versions studied except the two-person pressurized storable propellant concept. Here margins are large for the cryogenic landers. In the case of the storable propellant landers, the Dragon Propulsion Module can deliver all concepts except the two-person pressurized lander using current engines. Margins are unacceptably small for the two-person landers, however, but ample for the one-person concepts.

Finally, a Centaur III-equivalent stage delivered to LEO with full propellants by a Falcon Heavy is capable of delivering all lander concepts studied to LLO with 40% margin or more.

VII. Estimated Project Costs

We have roughly estimated both the non-recurring costs to develop the necessary flight and ground systems, crew training, and communications, the cost of the flight program, and the business and management costs of a PSLR project using the Falcon Heavy scenario discussed above. The approximate non-recurring costs associated with this development are estimated as shown in Table 12.

Table 12

PSLR Project Cost Estimate: Non-Recurring

Development	
Study Phase	$0.05B
Lunar-Capable Dragon with Prop Module	$0.5B
Lander	$0.5B
Centaur Integration to FH	$0.2B
Crew Suits and Systems	$0.1B
Mission Control, Communications	$0.05B
Crew and Training	$0.1B
Management and Systems Integration	$0.2B
Business/Marketing/Public Outreach	$0.1B
30% Reserves	$0.55B
Total Development Cost	**$2.35B**

To then achieve first landing, the estimated cost of a 4-test mission suite and a complete spare mission flight set to account for a repeated test mission is very approximately as shown in Table 13.

Table 13

PSLR Project Cost ROM: Flight Project to First Landing

Lunar-Dragons on Falcon Heavy	\$1.05B
Centaur Upper Stages	0.50B
Landers on Falcon Heavy	\$1.05B
Suits and Crew Systems	\$0.20B
Mission Ops and Comm	\$0.25B
30% Reserves	\$0.95B
Total Flight Program Costs	**\$4.0B**

Hence we estimate that the entire PSLR project ROM cost—i.e., development plus flight program—totals to \$6.4B-including stated reserves to reach first landing. We further estimate that the price to repeat such lunar exploration missions and sustain a business is near \$1.5B.

It is natural to examine why PSLR can be conducted so inexpensively compared to the Constellation Program's former \$150B lunar-return price tag. Some reasons for this include:

- Leveraging extensive investments in vehicle development.
- Reduced requirements (e.g., 2 crew vs. 4, short sortie stays).
- Fixed-price contract assumptions and suppliers with demonstrated breakthrough price-point products: e.g., SpaceX's Falcon 9 and Dragon capsule.
- A shorter, more efficient development and flight test schedule.

- Efficient operations, focusing on the job itself, rather than on the number of jobs created.

VIII. Conclusions

The capability exists today for human return to the Moon for many purposes, and at costs more than an order of magnitude lower than those estimated for NASA’s now cancelled project Constellation.

Although new developments are required to enhance current/in-development launcher performance and Dragon performance, and to create a lunar lander, the scale, complexity, risks, and costs of such developments are far lower than starting from scratch to develop all new launch vehicles, a dedicated crew capsule, and landers with extensive capabilities not needed for simple early-Apollo class sortie missions.

Interim lunar flyby and orbital missions offer the possibility of beginning lunar operations before completing development of the lander and surface suits, thereby easing the funding required before revenue return can begin.

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