IAC-08-D2.8.5

C3 PERFORMANCE OF THE ARES-I LAUNCH VEHICLE AND ITS CAPABILITIES FOR LUNAR AND INTERPLANETARY SCIENCE MISSIONS

H. Dan. Thomas, Ph.D.
NASA Marshall Space Flight Center, USA
herbert.d.thomas@nasa.gov

ABSTRACT

NASA's Ares-I launch vehicle will be built to deliver the Orion spacecraft to Low-Earth orbit, servicing the International Space Station with crew-transfer and helping humans begin longer voyages in conjunction with the larger Ares-V. While there are no planned missions for Ares-I beyond these, the vehicle itself offers an additional capability for robotic exploration. Here we present an analysis of the capability of the Ares-I rocket for robotic missions to a variety of destinations, including lunar and planetary exploration, should such missions become viable in the future. Preliminary payload capabilities using both single and dual launch architectures are presented. Masses delivered to the lunar surface are computed along with throw capabilities to various Earth departure energies (i.e. C3s). The use of commercially available solid rocket motors as additional payload stages were analyzed and will also be discussed.

INTRODUCTION

As part of the Vision for Space Exploration [1], NASA is designing the Ares-I launch vehicle to deliver humans to the International Space Station and, in conjunction with the Ares-V, to the moon. This study considers alternate missions for the Ares-I and is a summary and extension of work performed at MSFC between 2006 and 2007 [2]. A preliminary analysis is performed to determine the vehicle's capabilities in delivering unmanned payloads to the lunar surface as well as to interplanetary destinations. Various lander propellant combinations are considered in delivering the lunar payloads. Also, commercially available solid rocket motors [3] are investigated to extend the potential throw masses to various Earth departure energies.

The recent success of autonomous rendezvous and docking [4] opens the possibility of using multiple launches to deliver payloads. This study explores the dual launch architecture, again using the Ares-I, and the corresponding increases to the lunar and interplanetary payload capabilities.

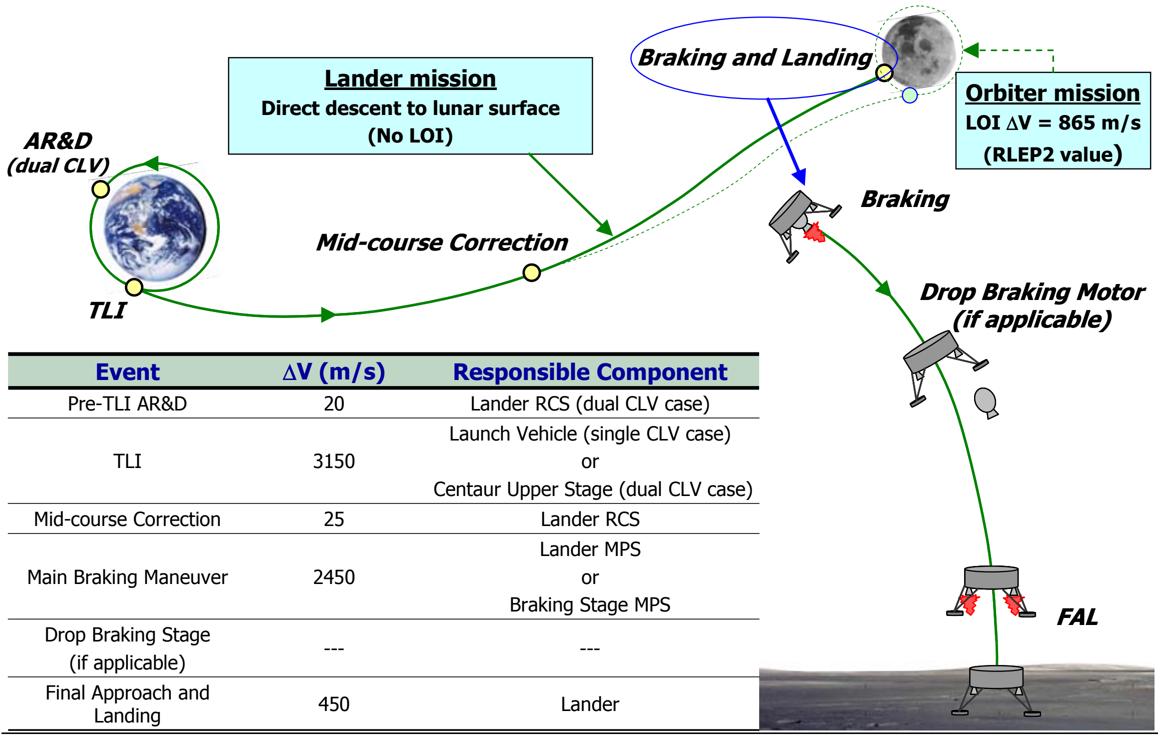
METHODOLOGY

Lunar Mission

The lunar mission results presented in this paper correspond to an older version of the Ares-I launch vehicle (CLV5, Rev2, DAC 1), which dates back to August of 2006. To the author's knowledge, this was the last Ares-I version for which trans-lunar injection (TLI) trades were performed. Once a new baseline vehicle is selected, new TLI capabilities can be determined.

The starting point for both the single and dual launch architectures is determining the mass that can be delivered to TLI. In the single Ares-I case, the launch vehicle delivers the payload directly to TLI, while the dual architecture explores the option of sending larger payloads by delivering the lander stack and a dedicated TLI stage in separate launches. The overall mission scenario and propulsive requirements are shown below in Figure 1. After TLI, the lander stack follows a direct-descent trajectory similar to that used in the Surveyor missions [5].

Once the TLI masses are known, the propellants are determined for various solid motor and lander propellant combinations. The lander propulsion options include monoprop hydrazine (N2H4), hypergolic biprop (fuel = N2H4 or MMH/oxidizer = N2O4), and cryogenic LH2/LOX systems (see Table 1 for specific impulse assumptions). After the lander propellant is computed, a mass estimating relationship is used to determine the corresponding dry mass of the lander. Then, the payload delivered to the lunar surface is computed by taking the difference between the sum of the known and estimated dry and propellant masses and the TLI start



Event	ΔV (m/s)	Responsible Component
Pre-TLI AR&D	20	Lander RCS (dual CLV case)
TLI	3150	Launch Vehicle (single CLV case) or Centaur Upper Stage (dual CLV case)
Mid-course Correction	25	Lander RCS
Main Braking Maneuver	2450	Lander MPS or Braking Stage MPS
Drop Braking Stage (if applicable)	---	---
Final Approach and Landing	450	Lander

Fig. 1: Lunar Mission Scenario and Propulsion Requirement Assumptions

mass. For missions with larger payload results, an orbiter may be delivered.

Lander Option	Isp (s)
Monoprop (N2H4)	MPS 230; RCS 230
Hypergolic Biprop (MMH/N2O4)	MPS 315; RCS 310
Cryogenic (LH2/LOX)	MPS 445 (during braking), 438 (during FAL); RCS 310

Table 1: Lander Specific Impulse (Isp) Assumptions

Single Launch Delivery to TLI

The single Ares-I delivery involves using the launch vehicle's second stage to perform the TLI maneuver. POST3D[6] is used to determine the optimal throw mass to an Earth orbit with a perigee altitude of 30 nautical miles (nmi) and a apogee that intersects the lunar orbit at 207,650 nmi. For this mission, an extended payload shroud of 1937 kg is assumed to allow larger payload elements. Table 2 lists the assumptions made in the single launch analysis. The resulting maximum TLI capability is 2516 kg, which includes the lander, payload, and any additional stages used during the lunar mission.

- Payload insertion: 30 nmi x 207,650 nmi
- LV Adapter to "payload" = 120 kg
- Extended shroud:
  - Length = 14.6 m
  - Diameter = 5.5 m
  - Mass = 1937 kg
  - Jettison at free molecular heating rate of 0.1 $BTU/(ft^2 \cdot s)$

Table 2: Earth-to-Orbit Assumptions used in the Single Ares-I Lunar Mission

Dual Launch Delivery to TLI

To increase the payload to the moon, the case of using two Ares-I launches is analyzed. The first launch sends the lander, payload, and any additional descent stages to low Earth orbit (LEO). The second launch delivers a Centaur IIIs stage with an extended mission kit. [7]. Both launches deliver to an intermediate 30 nmi x 160 nmi LEO. The Centaur performs its own circularization burn at 160 nmi, while an additional bipropellant kick motor is assumed to circularize the lander/braking stage stack.

This assumption may not be needed, since the lander engines can be placed far enough outboard to not interfere with the attached solid motor (this, hopefully, will be addressed in future work). With the above assumptions (listed in Table 3), the maximum delivery to TLI of the dual launch architecture is 15,575 kg.

- Payload insertion: 30 nmi x 160 nmi (circularize at 160 nmi)
- Larger extended shroud mass = 4330 kg
- First Launch:
  - – Lander, payload, and solid motor
  - – Kick motor for circularization
    - -- Isp = 300 s
    - -- Propellant Mass Fraction = 0.6
  - – Active docking interface = 800 kg
- Second Launch:
  - – Centaur III s
    - -- Burnout mass = 3050 kg
      - > Includes extended mission kit
      - > Includes 620 kg passive docking interface to lander
    - -- Available propellant = 20,175 kg
    - -- Isp = 451 s
    - -- LV adapter to Centaur = 4330 kg

Table 3: Earth-to-Orbit Assumptions Used in the Dual Ares-I Lunar Mission

Lander Mass Estimating Relationships

Now that the TLI start masses are determined, the remaining element needed to compute the payload capabilities of the various missions is the lander dry mass (for a given propellant load). The propellant mass fraction (PMF) is defined as the ratio of the total propellant mass (m_p) to the total mass of the lander. A useful relationship to between PMF and m_p is:

$$PMF = \frac{a}{1 + \frac{b}{\left(\frac{m_p}{kg}\right)^c}}$$

where a, b, and c are parameters that can be used to "curve-fit" the equation to a given set of data. If one then assumes that the total mass is sum of the propellant and dry masses, which in this case is really the inert mass, then the following is true:

$$m_{dry} = m_p \left(\frac{1}{PMF} - 1\right)$$

These equations are used to determine the lander dry mass as a function of propellant. Table 4 lists the curve-fit constants that are used to estimate the various lander masses. The corresponding PMF and dry mass variations are shown in Figures 2 and 3, respectively, for the monoprop/hypergolic lander. Figures 4 and 5 show the curve-fits for the LH2/LOX propellant lander. Note that the PMF values for the cryogenic lander is lower than the hypergol lander. This is due to use of pressure vessel tanks, instead of structural tanks, which is assumed to be valid considering the cryogenic propellant loads of interest (~ 1000 to 8000 kg).

Propellant Mass Fraction Relationship

$$PMF = \frac{a}{1 + \frac{b}{\left(\frac{m_p}{kg}\right)^c}}$$

Monoprop or Hypergolic Biprop Lander	Cryogenic LH2/LOX Lander
a = 0.9785	a = 0.8637
b = 40.7288	b = 20.3612
c = 0.57	c = 0.45

Table 4: PMF Curve-fit Parameters for Monoprop/ Hypergolic Biprop and Cryogenic Landers

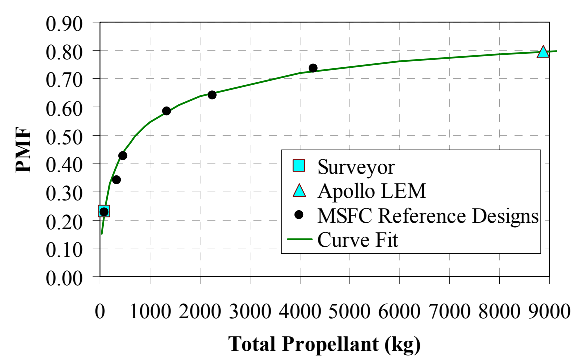


Fig. 2: Variation of PMF with Propellant for Landers with Monopropellant or Hypergolic Bi-propellant Propulsion Systems

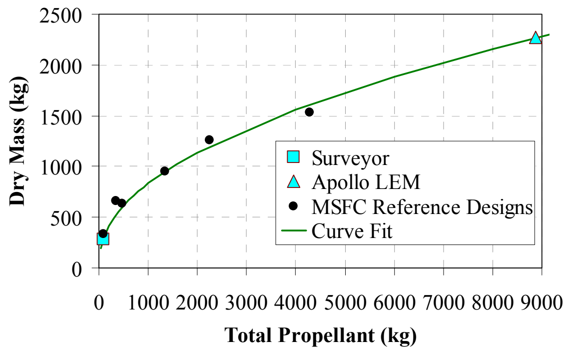


Fig. 3: Relationship of Dry Mass to Propellant Mass for Lander with Monopropellant or Hypergolic Bi-propellant Propulsion Systems

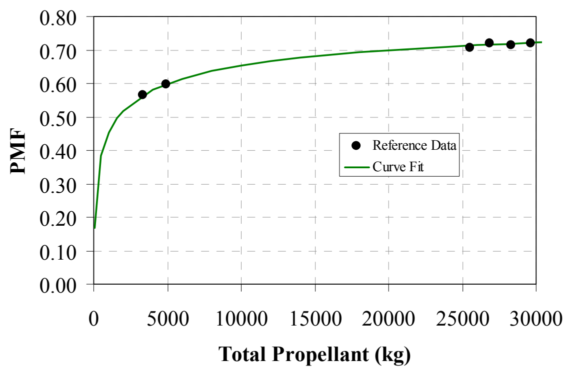


Fig. 4: Variation of PMF with Propellant for Landers with LH2/LOX Propulsion Systems (Pressure-vessel Tanks)

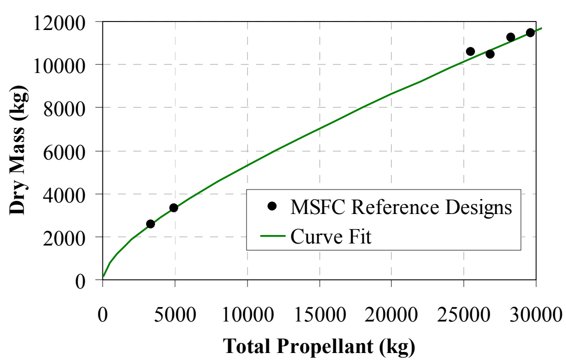


Fig. 5: Variation of PMF with Propellant for Landers with LH2/LOX Propulsion Systems (Pressure-vessel Tanks)

Interplanetary Missions

Finally, the single and dual launch options are also considered for use in delivering payloads (i.e. spacecraft) to higher energy Earth orbits, including escape. For the dual Ares-I case, the same assumptions given above are applied here, with the option of using an additional solid motor to assist the Centaur in the orbit-raising maneuver. If a solid motor is used, then an extra adapter mass of 500 kg is assumed.

For the single Ares-I launch, an updated vehicle is used (CLV 5P-1), which is capable of injecting 24.1 mT into an 11 nmi x 100 nmi LEO; the injection altitude is 83.2 nmi. From this point, a solid motor is used for the Earth-departure maneuver. The 24.1 mT includes the solid motor(s), spacecraft, and a 400 kg adapter between the solid motor and spacecraft. If two solid motors are used, then an interstage with a mass of 600 kg is included.

At this time, no consideration is given to how the larger solid motors, not to mention multiple motors, will fit into the Ares-1 shroud. Also ignored are the maximum offloads allowed by the various solid motors.

RESULTS

Lunar Mission

Given the mission and lander assumptions outlined in the previous section, one can now compute the payloads delivered to the lunar surface. For the single launch architecture, the results are shown in Figure 6. A total of four cases are given. The first two correspond to the option where the lander propulsion system is responsible for the entire descent and landing (cryogenic and hypergol, respectively). The remaining two cases use a solid braking motor to remove the majority of the lander's energy at the moon, with the onboard propulsion system performing the final landing burn.

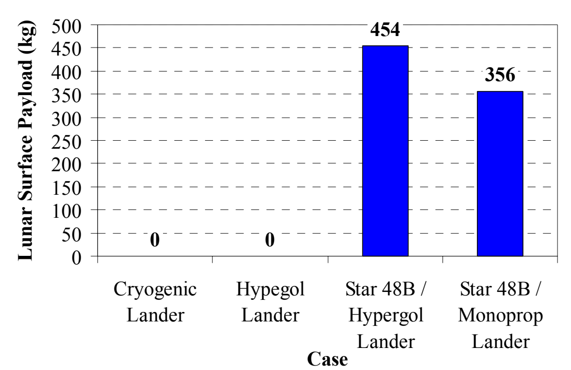


Fig. 6: Payload Delivered to the Lunar Surface for the Single Launch Architecture

As shown, the use of solid braking motors is required to deliver a payload to the lunar surface for the given

TLI throw mass of 2516 kg. The bi-propellant option delivers 454 kg, while the monoprop system lands 356 kg of payload. Both require the use of a Star 48B motor. The propellant results and dry (i.e. inert) mass approximations are given below in Tables 5 and 6. Even though the biprop shows more capability than the monoprop, the monoprop may be the more desirable option due to the simplicity, reliability, and lower cost of this system. Also, monoprop system dry mass savings may be realized that are not accounted for in the mass estimating relationship. The solid motor/cryogenic lander case is not considered a viable option due to the relatively low propellant requirements and the large dry mass penalties of a LH2/LOX propulsion system (compared to storable propellant systems).

Star 48B	
Item	Mass (kg)
Inert	117
MPS Propellant	1446
RCS Propellant	0
Total	1563
Hypergol Lander	
Item	Mass (kg)
Inert	344
MPS Propellant	133
RCS Propellant	22
Total	499
Delivered Payload	**454 kg**

Table 5: Delivered Masses for the Hypergol Lander Option of the Single Launch Lunar Mission

Star 48B	
Item	Mass (kg)
Inert	117
MPS Propellant	1446
RCS Propellant	0
Total	1563
Monoprop Lander	
Item	Mass (kg)
Inert	390
MPS Propellant	178
RCS Propellant	29
Total	597
Delivered Payload	**356 kg**

Table 6: Delivered Masses for the Monoprop Lander Option of the Single Launch Lunar Mission

The dual Ares-I architecture delivers a much larger mass to TLI (15,575 kg). This permits the use of not only cryogenic propulsion systems, but also allows the lander to perform the entire descent maneuver. As with the single launch mission, it is assumed that the propellant required for the solid motor/cryogenic combination is not large enough to warrant consideration of a LH2/LOX propulsion system. The reduced propellant amount due to the increased Isp is not enough to overcome the mass penalty associated with the cryogenic propulsion system.

Figure 7 shows the cases with the maximum deliveries to the lunar surface, and Tables 7 through 10 list the corresponding inert and propellant masses. A LH2/LOX lander, without solid motors, places 3026 kg on the moon, while the bipropellant hypergol lander has a payload of 3175 kg. For the lander-only missions, the propellant requirements are not large enough for the cryogenic lander to outperform the hypergol system. As before, staging the descent burn increases the payload amounts. Using an Orbus 21, the storable landers deliver maximum payloads of 4121 kg for the biprop system and 3655 kg for the monoprop alternative. In this case, the 466 kg of additional payload capability of the biprop option most-likely outweighs the simplicity/cost benefit of the monoprop propulsion system.

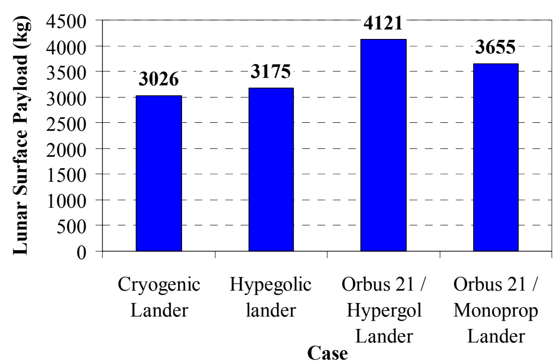


Fig. 7: Payload Delivered to the Lunar Surface for the Dual Launch Architecture

Cryogenic Lander	
Item	Mass (kg)
Inert	4494
MPS Propellant	7809
RCS Propellant	245
Total	12,549
Delivered Payload	**3026 kg**

Table 7: Delivered Masses for the Cryogenic Lander Option (no Solid Braking Motor) of the Dual Launch Lunar Mission

Hypergol Lander	
Item	Mass (kg)
Inert	2378
MPS Propellant	9777
RCS Propellant	245
Total	12,400
Delivered Payload	**3175 kg**

Table 8: Delivered Masses for the Hypergolic Lander Option (no Solid Braking Motor) of the Dual Launch Lunar Mission

Orbus 21	
Item	Mass (kg)
Inert	689
MPS Propellant	8917
RCS Propellant	0
Total	9606
Hypergol Lander	
Item	Mass (kg)
Inert	769
MPS Propellant	834
RCS Propellant	245
Total	1848
Delivered Payload	**4121 kg**

Table 9: Delivered Masses for the Hypergolic Lander/Orbus 21 Option of the Dual Launch Lunar Mission

Orbus 21	
Item	Mass (kg)
Inert	689
MPS Propellant	8917
RCS Propellant	0
Total	9606
Monoprop Lander	
Item	Mass (kg)
Inert	874
MPS Propellant	113
RCS Propellant	327
Total	2314
Delivered Payload	**3655 kg**

Table 10: Delivered Masses for the Monoprop Lander/Orbus 21 Option of the Dual Launch Lunar Mission

Interplanetary Missions

Another possible use of the Ares-I is for unmanned missions to interplanetary destinations. All launch energy (i.e. C3) analyses performed in this report utilize dedicated Earth-departure stages. In the dual launch architecture, the first launch orbits the science payload (i.e. spacecraft) and optional solid motor followed by the Centaur IIIs in the second launch. The mission is assumed to depart from a 160 nmi LEO. Figure 8 shows the dual-launch thrown payload as a function of C3 for various combinations of departure stages. These are compared to current missions sent, or in route to, different destinations, including Mercury (Messenger), Mars (Mars Phoenix), and Pluto (New Horizons). A significant mass can be delivered to the inner planets, even without additional solid motors. However, large solid stages are required to match the Earth-departure energy of the New Horizons spacecraft. The Centaur/Star 48B combination comes close but does not have enough propellant to achieve the same mission.

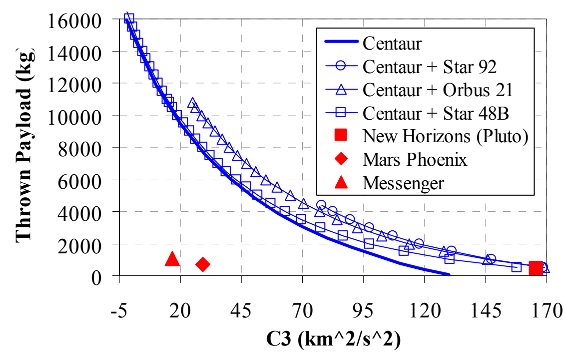


Fig. 8: Delivered Spacecraft Masses to Various Earth Departure Energies for the Dual Launch Architecture

The single launch throw capability is shown in Figure 9. Here, an updated version of the Ares-I vehicle is used that delivers 24,100 kg (without shroud) to an 11 nmi x 100 nmi Earth orbit. The departure burn occurs at an altitude of 83.2 nmi. For this case, a Star 63F delivers sizable payloads to the inner planets with only slightly less masses than the Messenger and Mars Phoenix spacecraft. Utilizing larger motors, such as the Orbus 21 and Star 92, allows much more mass to be delivered but may exceed the structural limits of the vehicle as well as the payload shroud volume. Multiple solid combinations are also considered with the goal of matching the New Horizons mission delivery. However, the 24.1 mT start mass limits the viable stage combinations, and the maximum departure energy falls well short of the Pluto mission.

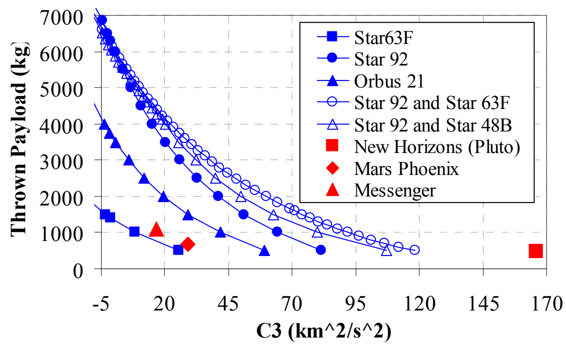


Fig. 9: Delivered Spacecraft Masses to Various Earth Departure Energies for the Updated Single Launch Architecture

CONCLUSIONS

The Ares-I version that is analyzed in this report provides a viable solution to sending unmanned payloads to the moon. Up to 454 kg (in addition to the lander mass) can be placed on the lunar surface by performing the direct descent at the moon with a staged Star 48B motor followed by the storable biprop lander propulsion system. With a more simple and less costly monoprop system (again with a Star 48B), a comparable amount of 356 kg can be landed.

Utilizing two Ares-I launches (with one launch delivering a LH2/LOX TLI stage) can deliver a much larger payload of 4121 kg, assuming that the Orbus 21 braking stage does not exceed the Ares-I structural and volume limits. This increased payload also expands the types of missions that can be achieved. For example, a communications/relay satellite can be delivered to lunar orbit along with a sizable surface payload. Also, a sample return mission may be possible (further investigation required).

The Ares-I vehicle also can send sizable payloads to various interplanetary destinations. Using a departure solid motor larger than the Star 63F allows a significant mass to be sent to the inner planets and the main asteroid belt (C3 to Ceres ~ 38 km^2/s^2) with only a single Ares-I launch. A dual-launch solution with the Centaur departure stage increases the throw capability by a large margin. Staging an additional solid motor allows deliveries approaching and matching that of the New Horizons mission to Pluto. Therefore, not only can the Ares-I help achieve NASA's human exploration goals, but it can also supplement the launch options for interplanetary missions.

REFERENCES

[1] President George W. Bush, *The Vision for Space Exploration*, January 14, 2004, http://www.nasa.gov/mission_pages/exploration/main/index.html.

[2] Thomas, H.D. and McKamey, S., "Unmanned Payload Capabilities of Single and Dual Launch CLV Missions", Internal Study to Advanced Concepts Office, NASA Marshall Space Flight Center, September 2008 (updated October 2007).

[3] *ATK Space Propulsion Products Catalog*, Alliant Techsystems, Inc, May 2008, http://www.atk.com/Customer_Solutions_MissionSystems/documents/ATK_Catalog_May_2008.pdf

[4] http://www.esa.int/SPECIALS/ATV/index.html

[5] "Surveyor Spacecraft A-21 Model Description", NASA-CR-84185, Jet Propulsion Laboratory, March 1965.

[6] Powell, R. W., Striepe, S. A., Desai, P. N., Braun, R. D., *Program to Optimize Simulated Trajectories (POST)*, NASA Langley Research Center, Oct. 1997.

[7] McKamey, S., Personal Communication, September 8, 2006.

C3 Performance of the ARES-I Launch Vehicle and Its Capabilities for Lunar and Interplanetary Science Missions

Dan Thomas
ED04: Advanced Concepts Branch
NASA Marshall Space Flight Center, AL 35812

presented by

Gary Lyles
ED01: Engineering Directorate, Associate Director
NASA Marshall Space Flight Center, AL 35812

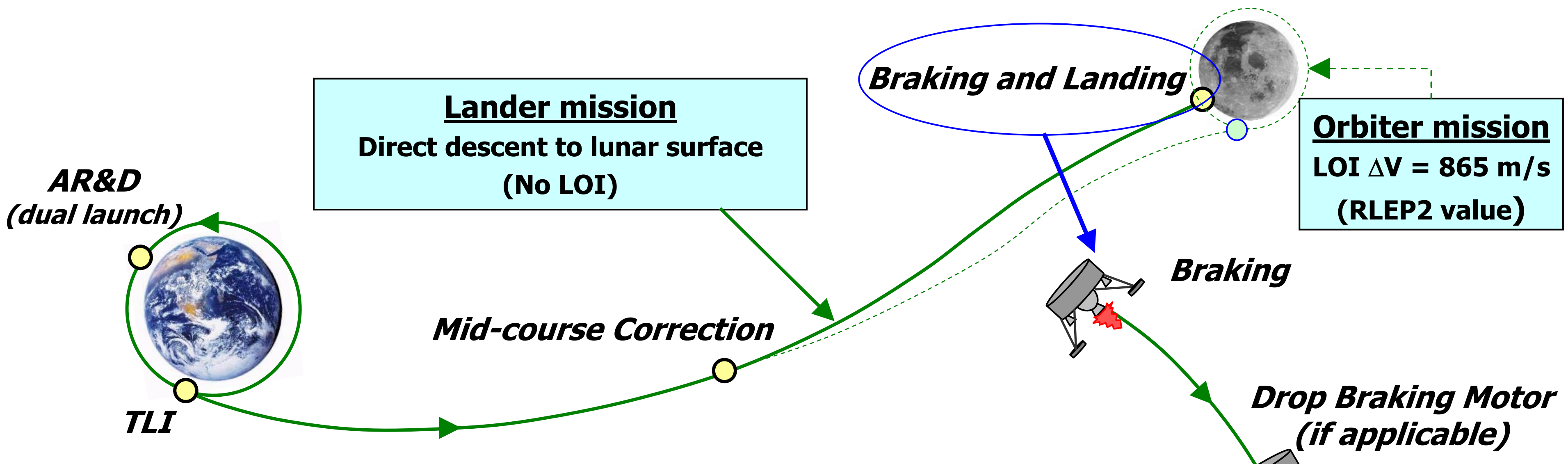
10/02/2008

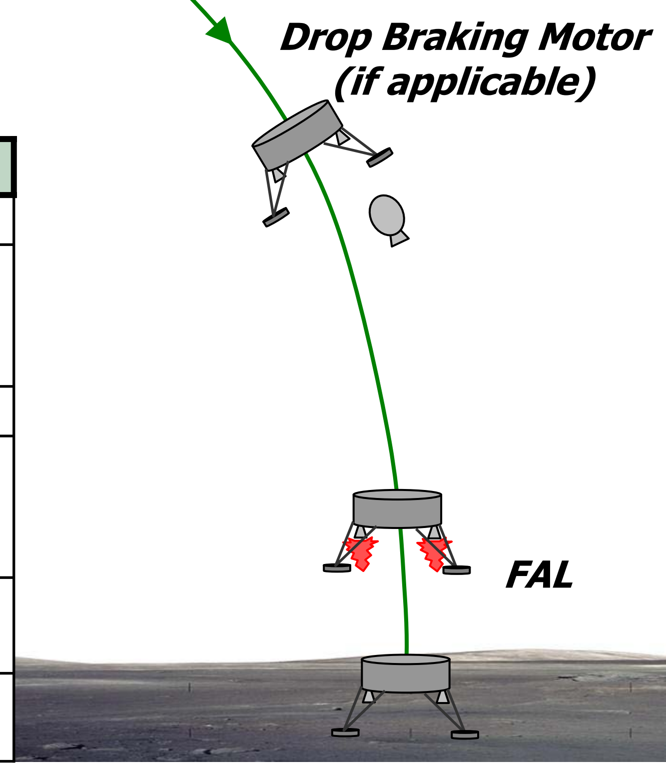
Objectives

- **Examine capabilities of Ares-I to deliver unmanned, lunar surface payloads**
  - Single Launch (using Ares-I second stage for TLI)
    - ***Throw mass to TLI: 2516 kg***
  - Dual Launch
    - Lander
    - Centaur upper stage
      - ***With extended mission kit***
    - Rendezvous and dock in LEO
    - Centaur delivers lander to TLI and is jettisoned
    - ***Throw mass to TLI: 15,575 kg***
  - Lander propulsion systems considered
    - Cryogenic: LOX/LH2 (for systems with larger propellant loads)
    - Hypergol: N2O4/MMH
    - Monoprop: Hydrazine
  - With and without solid braking stage during lunar descent
  - Utilize propellant mass fraction relationships to estimate lander dry masses

- **Examine potential science mission deliveries to various launch energies (i.e. C3s)**

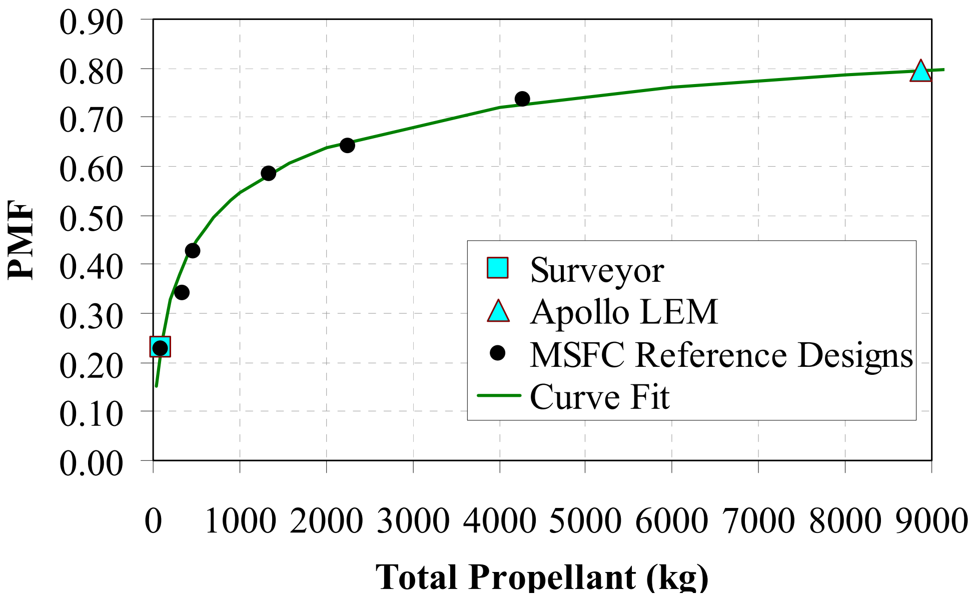
Lunar Mission Description

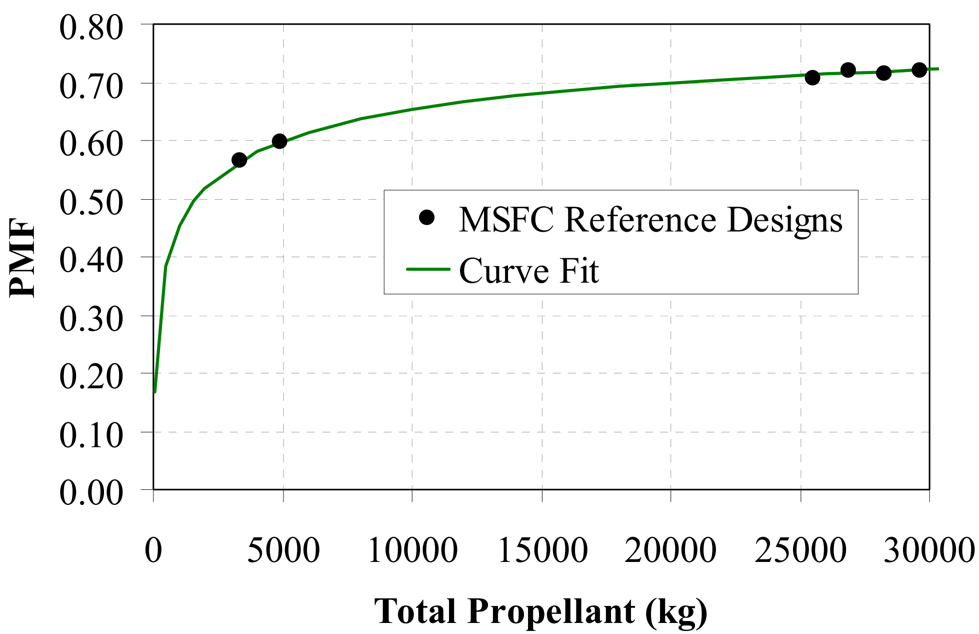




Event	ΔV (m/s)	Responsible Component
Pre-TLI AR&D	20	Lander RCS (dual launch case)
TLI	3150	Launch Vehicle (single launch case) or Centaur Upper Stage (dual case)
Mid-course Correction	25	Lander RCS
Main Braking Maneuver	2450	Lander MPS or Braking Stage MPS
Drop Braking Stage (if applicable)	---	---
Final Approach and Landing	450	Lander

Other Assumptions





$$PMF = \frac{m_p}{m_p + m_{dry}} = \frac{a}{1 + \frac{b}{\left(\frac{m_p}{kg}\right)^c}}$$

Monoprop or Hypergolic Biprop Lander

a = 0.9785
b = 40.7288
c = 0.57

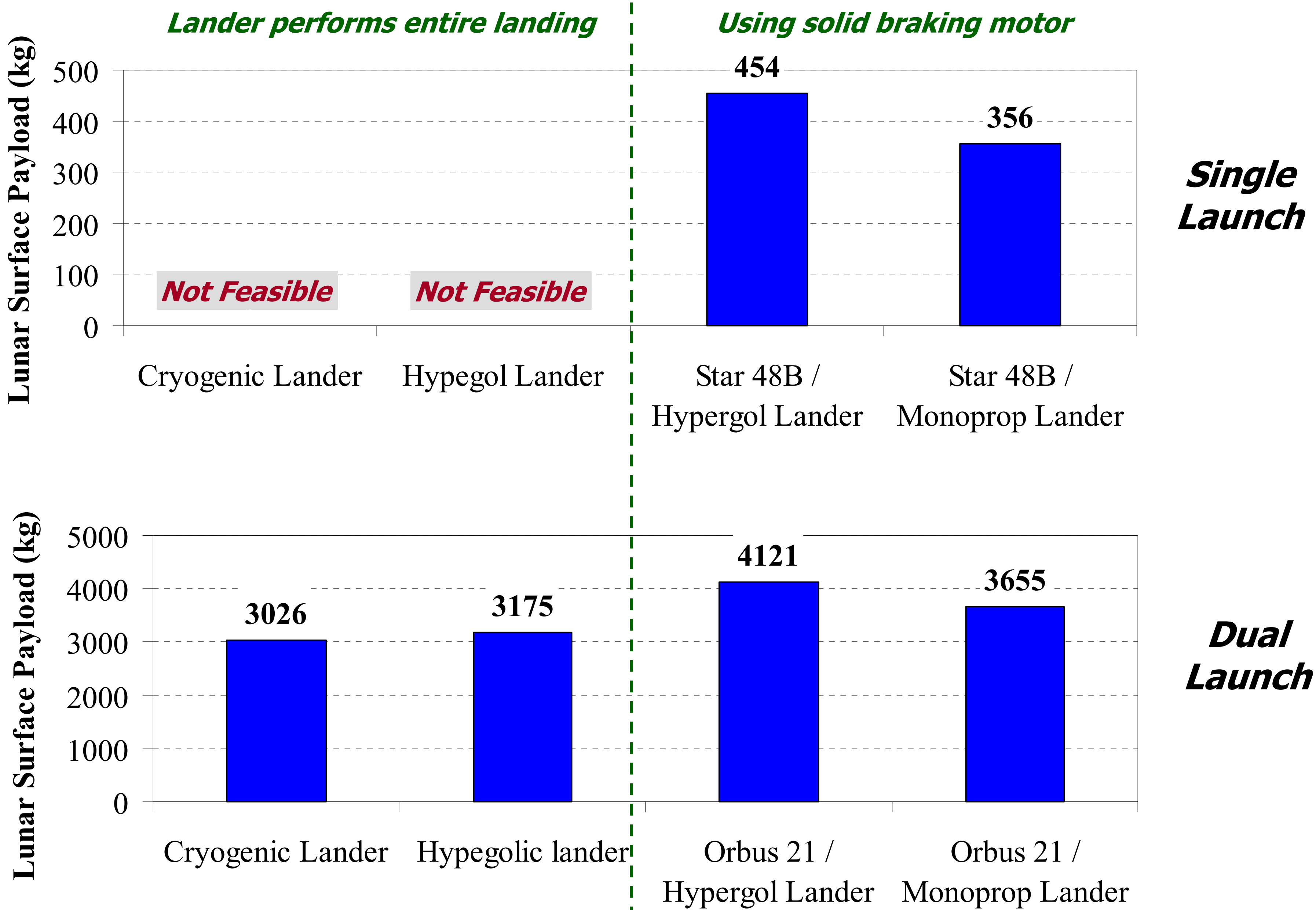
Monoprop: Isp_{MPS} = 230 s
Isp_{RCS} = 230 s
Biprop: Isp_{MPS} = 315 s
Isp_{RCS} = 310 s

Cryogenic LH2/LOX Lander

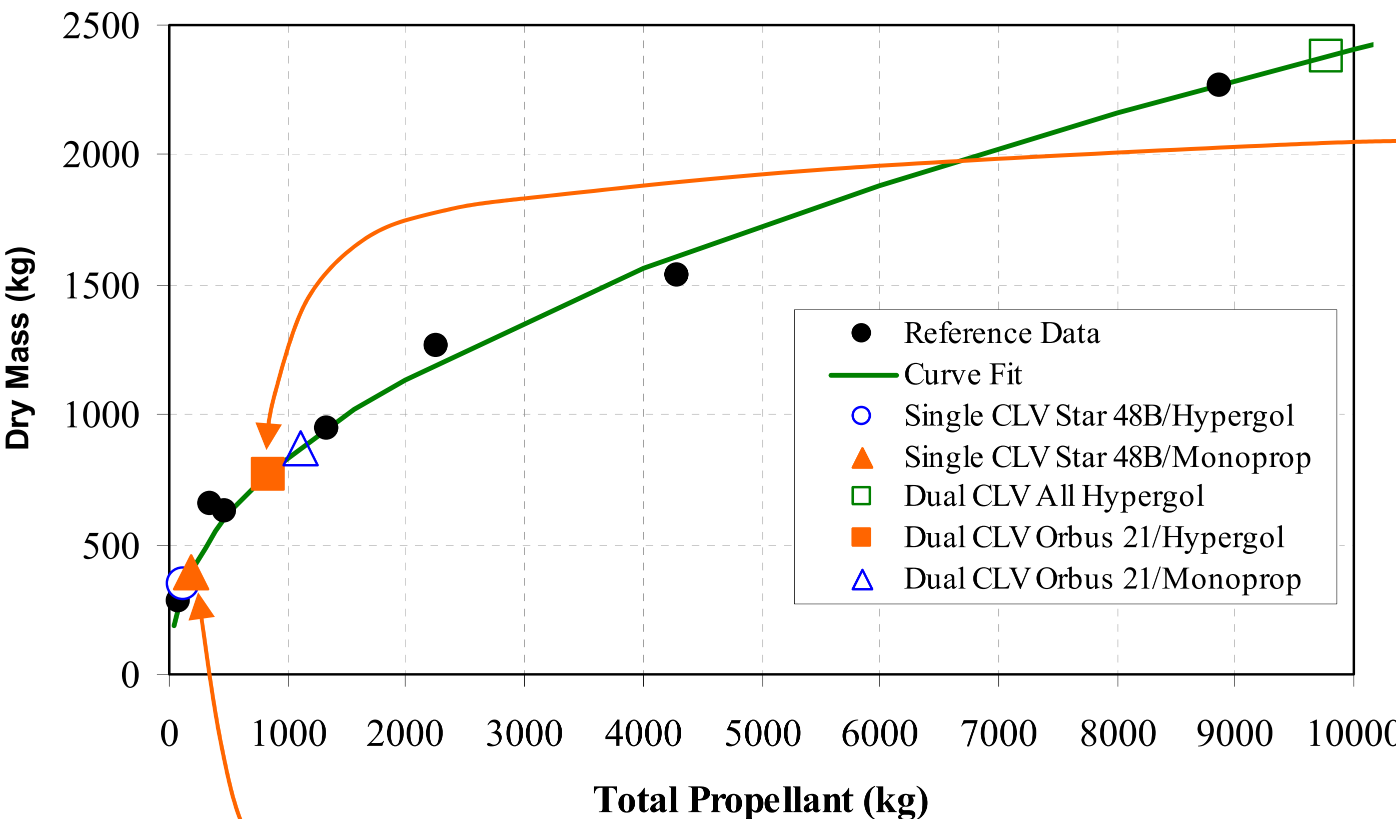
a = 0.8637
b = 20.3612
c = 0.45

Isp_{MPS} = 445 s (during braking)
= 438 s (during final landing)
Isp_{RCS} = 310 s

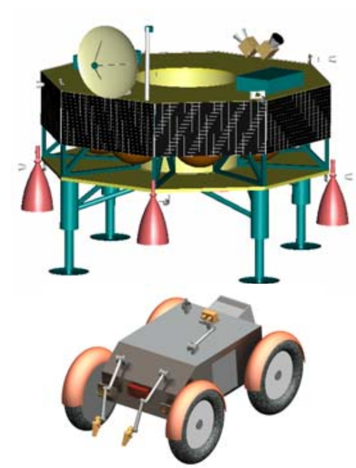
Delivered Lunar Surface Payloads
Single and Dual Launch Results



Storable Propellant Lander Options



Dual Ares-I



Larger Payload

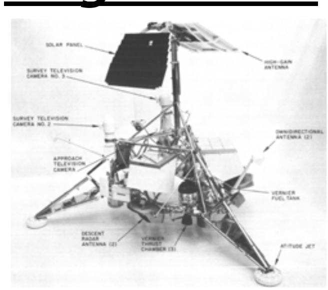
(~4100 kg)

- Larger Rover(s)
- Additional payload

or

Sample Return ?

Single Ares-I



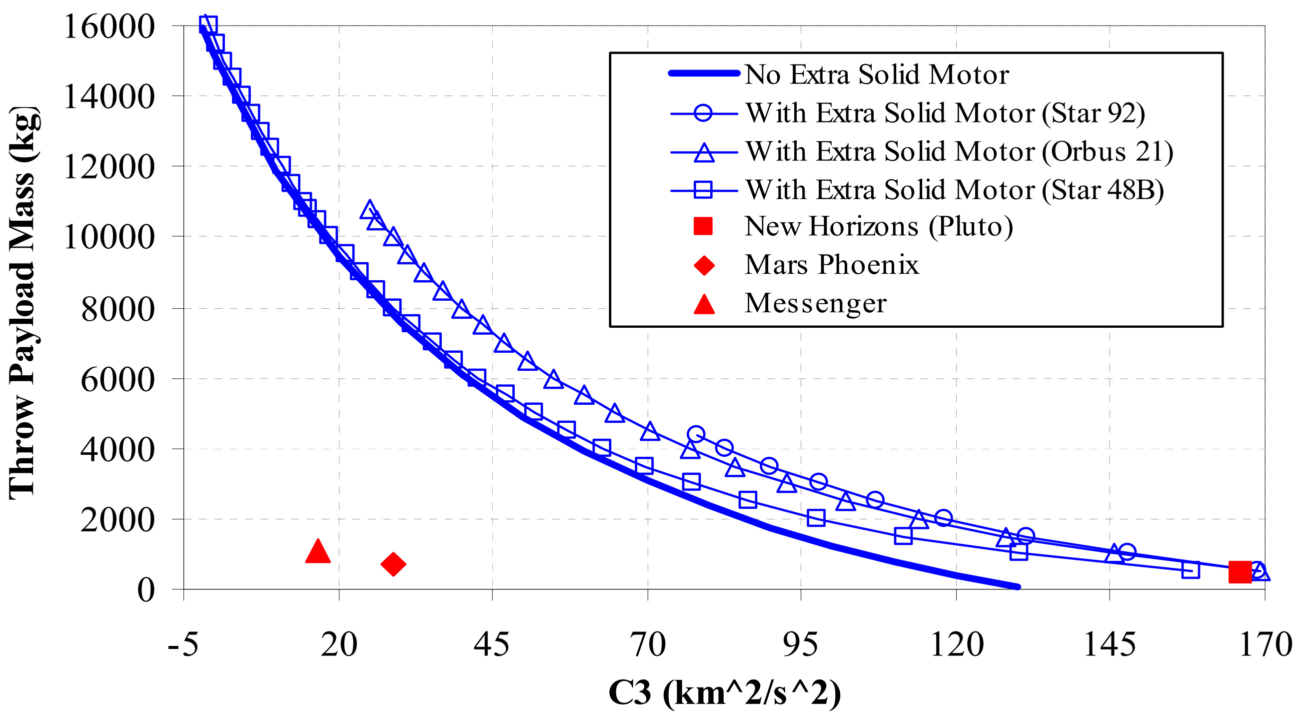
Small Payload

(~350-450 kg)

- Slightly larger than Surveyor
- Small rover or science package

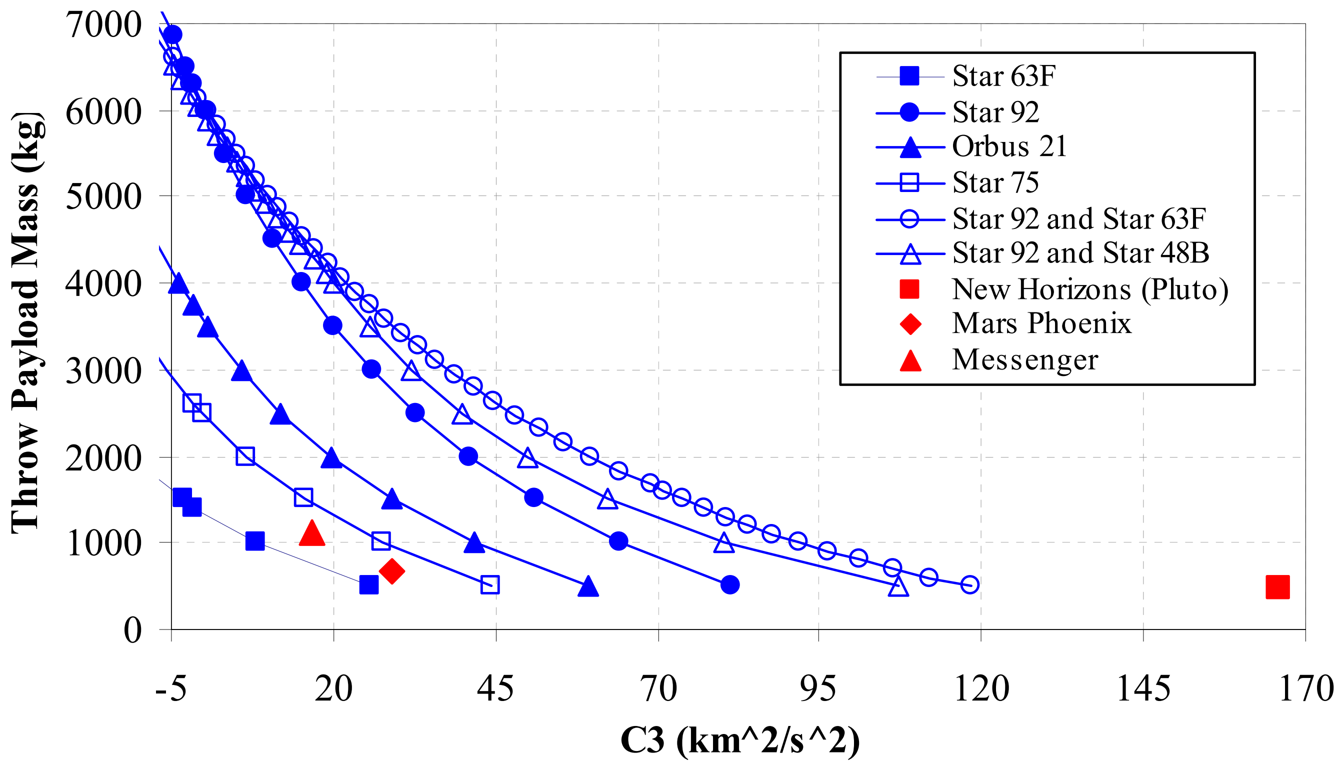
Interplanetary Capability
Dual Launch

- **Assumptions**
  - First Launch includes payload and extra solid kick motor (and adapters)
  - Second launch includes Centaur (and adapters)
  - No consideration given to possible shroud size increases (over previous dual-launch assumptions)
- **Oberservations**
  - Can send sizable payloads to inner planets and main belt asteroids
  - Can match recent outer planet, high energy mission (i.e. New Horizons to Pluto)



Interplanetary Capability

Single Launch (newer version) with Kick Stage



- **Ares-I injects 24.9 mT into 11 x 100 naut. mi. LEO *(Newer version: CLV 5P-1)***
  - Includes LV adapter (dropped after LEO injection) and "payload" mass
  - Injection at 83.2 naut. mi.
- **TLI capabilities**
  - Using Star 92: 6300 kg *[Atlas V (541) = 6030 kg; Atlas V (551) = 6560 kg]*
  - Using Orbus 21: 3740 kg *[Atlas V (401) = 3580 kg; Atlas V (511) = 3915 kg]*
- **Interplanetary mission options**
  - Inner planets and main asteroid belt (e.g. C3 to Ceres ~ 38 km2/s2)

Conclusions and Recommendations
Lunar Surface Deliveries

- **Single Ares-I launch**
  - Small monoprop or biprop lander: payload ~ 350-450 kg
  - Lunar orbiter on-orbit mass ~ 1750 kg
    - Provides communication relay to lunar surface assets
    - May include additional instruments for scientific observations
    - May allow more than one communication relay satellite ?
  - Larger capabilities may be possible with dedicated TLI stage

Only one option per launch (applies to the lander and orbiter items)

- **Dual Ares-I launch**
  - Hypergol bi-prop lander: payload ~ 4100 kg
    - Larger payloads possible with new, specialized solid motor
  - Increased payload options
    - Large science payload
    - Larger rover(s)
    - Possible sample return?
    - Dual lander/orbiter mission?
      - For ~ 500 kg orbiter (comm. relay sat), can still land ~3550 kg surface payload
      - Larger orbiters may be launched at the expense of landed surface payload

Requires further investigation (applies to larger rover(s), possible sample return, and dual lander/orbiter mission)

Conclusions and Recommendations
Non-lunar Science Potential

- **Dual Ares-I launch**
  - Large range of interplanetary missions
  - Very large mass delivered to inner planets and main-belt asteroids
    - Without need for solid kick motor (in addition to Centaur stage)
  - Potential for outer-planet missions
    - Requires additional solid motor

- **Single Ares-I launch**
  - Larger solid motors required for significant throw mass
  - Can deliver masses comparable to recent inner planet missions
  - Potential for main-belt asteroid mission