Ares V launch vehicle: An enabling capability for future space science missions

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Abstract

NASA’s planned Ares V cargo launch vehicle offers the potential to completely change the paradigm of future space science mission architectures. Future space science telescopes desire increasingly larger telescope collecting aperture. But, current launch vehicle mass and volume constraints are a severe limit. The Ares V greatly relaxes these constraints. For example, while current launch vehicles have the ability to place a 4.5 m diameter payload with a mass of 9400 kg on to a Sun-Earth L2 transfer trajectory, the Ares V is projected to have the ability to place an 8.8 m diameter payload with a mass of approximately 60,000 kg on to the same trajectory, or 180,000 kg into Low Earth Orbit. Also the Ares V could place approximately 3000 kg (13,000 kg with a Centaur upper stage) on to a trajectory with a C3 of 106 km²/s², arriving at Saturn in 6.1 years without the use of gravity assists. This paper summarizes the current planned Ares V payload launch capability.

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1. Introduction

For over 30 years, science mission capabilities have been constrained by launch vehicles. The Hubble Space Telescope and Chandra X-ray telescope were specifically designed to match the Space Shuttle’s payload volume and mass capacities (Table 1, Fig. 1). (Note: Hubble was actually sized based on maximum abort landing mass.) And the James Webb Space Telescope is currently being designed to match the capacities of an Ariane 5 (Table 2, Fig. 2). Similarly, launch vehicle capabilities constrain mass and flight times for missions to the outer planets. For example, the New Horizons mission, the fastest spacecraft ever launched, will take 9.5 years to deliver its 480 kg science payload to Pluto. But, maybe more importantly, launch vehicle constraints drive mission complexity, risk and cost as mission planners attempt to package increasingly more scientifically capable missions into existing launch vehicles.

Currently, these challenges are being overcome by fabricating systems with lower areal densities and complex packaging configurations. For example, Hubble with its single monolithic 2.4 m diameter primary mirror and total spacecraft diameter of 4.3 m was specifically designed to fit inside the Shuttle 4.6 m payload bay. But, JWST must fold its 6.5 m diameter primary mirror in a ‘drop-leaf’ configuration to fit into the 4.57 m diameter Ariane 5 shroud. Additionally, Hubble’s optical telescope assembly weighed slightly less than 2400 kg
Table 1
Space shuttle launch capabilities vs. science missions requirements.

<table>
<thead>
<tr>
<th></th>
<th>Payload mass (kg)</th>
<th>Payload volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space shuttle capabilities</td>
<td>25,061 (max at 185 km)</td>
<td>4.6 m×18.3 m</td>
</tr>
<tr>
<td></td>
<td>16,000 (max at 590 km)</td>
<td></td>
</tr>
<tr>
<td>Hubble space telescope</td>
<td>11,110 (at 590km)</td>
<td>4.3 m×13.2 m</td>
</tr>
<tr>
<td>Chandra X-ray telescope (and Inertial upper stage)</td>
<td>22,800 (at 185km)</td>
<td>4.3 m×17.4 m</td>
</tr>
</tbody>
</table>

Fig. 1. Hubble Space Telescope and Chandra X-ray Telescope were specifically designed to fit inside the Space Shuttle Payload Bay.

Table 2
Ariane 5 Launch capabilities vs. JWST science missions requirements.

<table>
<thead>
<tr>
<th></th>
<th>Payload mass (kg)</th>
<th>Payload volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ariane 5</td>
<td>6600 (at SE L2)</td>
<td>4.5 m×15.5 m</td>
</tr>
<tr>
<td>James Webb Space Telescope</td>
<td>6530 (at SE L2)</td>
<td>4.47 m×10.66 m</td>
</tr>
</tbody>
</table>

Fig. 2. 6.5 m diameter JWST is folded like a drop-leaf table to fit inside the 4.5 m Ariane 5 launch shroud.
for an areal density of 590 kg/m²; its primary mirror assembly weighed slightly more than 1860 kg for an areal density of 460 kg/m² and its primary mirror weighted approximately 740 kg for an areal density of 180 kg/m² [1]. By comparison, the entire JWST optical telescope assembly is required to weigh less than 2500 kg for an areal density of 100 kg/m². A single primary mirror segment assembly, of which the JWST primary mirror has 18, has an areal density of approximately 30 kg/m². And, the primary mirror with its back plane support structure has a combined areal density of approximately 70 kg/m².

While significant technical challenges have been met and overcome to package the 6.5 m JWST into a 5 m class launch vehicle, an entirely new approach is required for the desired larger aperture systems of the future. A major finding of the NASA Advanced Telescope and Observatory Capability Roadmap Study [2–5] was that this need could be achieved by developing even lower areal density mirrors or more sophisticated packaging and deployment schemes or on-orbit assembly or synthetic aperture formation flying or a larger launch vehicle.

2. Ares-V launch capability

NASA’s Ares V cargo launch vehicle, planned to enter service between 2018 and 2020, will be a disrupting capability that promises to completely change the paradigm of future space science missions. It has the potential to revolutionize space astronomy by being able to place into orbit far more volume and mass than any existing system (Table 3) [6–11]. It should be noted that the Ares V configuration is under constant development. The configuration discussed in this paper is primarily LV 51.00.48. But, most of the performance information presented is for configuration LV 51.00.39. The capabilities of LV 51.00.48 will be given when known.

The Ares V launch vehicle (LV 51.00.48) shown in Fig. 3 is a 10 m diameter 116 m tall rocket with a core stage and an upper stage. The core stage has six RS-68 engines and two 5.5-segment solid rocket boosters (SRBs). (The previous LV 51.00.39 configuration only had five RS-68 engines and two 5-segment SRBs.) The upper stage uses a single J-2X LOX/LH2 engine. The gross liftoff mass is 3700 mT. The extra propulsion provides a payload mass capability of ~62.8 mT to direct trans-lunar insertion (TLI) orbit and ~187.7 mT to low Earth orbit (LEO).

The current baseline Ares V shroud is a biconic fairing with a 10 m outer diameter and 23 m height. As summarized in Fig. 4, this shroud has an 8.8 m dynamic inner envelope diameter, a 17.2 m envelope height and a payload volume of 860 m³—which is nearly three times the 300 m³ volume of the Space Shuttle payload bay. A ‘stretch’ fairing is being considered that is 26 m tall with 1410 m³ of volume. Finally, a serious trade is underway to study the impact of replacing the biconic noise cone with an ogive shape. The NASA MSFC Advanced Concepts Office analyzed the Ares V launch environment for several ascent profiles using POST3D (program to optimize simulated trajectories—3 dimensional), LAV (launch vehicle analysis) and other tools. The maximum launch loads for the Ares V (summarized in Table 4) are similar to those of existing launch vehicles. Please note that the maximum loads shown in Table 4 are not concurrent and are for the center of mass of the launch vehicle—not for the payload volume. Launch loads are separated into quasi-steady state and dynamic loads. Adding the steady-state and dynamic values gives an estimated maximum load for the axial and lateral directions. While the maximum axial loads occur immediately prior to main engine cut-off (MECO) of the core stage, the maximum lateral loads are from wind buffeting and can occur anywhere during the lower portion of the ascent. Regarding peak acoustic loads within the payload volume, preliminary analysis done at NASA’s Glenn Research Center indicates values of 145–150 db are likely immediately after lift-off. In addition to these load

<table>
<thead>
<tr>
<th>Fairing Dia. (m)</th>
<th>Payload volume</th>
<th>Mass (kg) to LEO</th>
<th>Mass (kg) to GTO</th>
<th>Mass (kg) to GEO</th>
<th>Mass (kg) to L2</th>
<th>Mass (kg) to Escape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space Shuttle</td>
<td>4.6 m x 18.3 m</td>
<td>25,061</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Ariane 5 ECA</td>
<td>5</td>
<td>21,000</td>
<td>10,500</td>
<td>NA</td>
<td>6600</td>
<td>4300</td>
</tr>
<tr>
<td>Atlas V HLV</td>
<td>5</td>
<td>29,420</td>
<td>13,000</td>
<td>6350</td>
<td>9160</td>
<td>9035</td>
</tr>
<tr>
<td>Delta IV H</td>
<td>5</td>
<td>22,950</td>
<td>12,650</td>
<td>6160</td>
<td>9410</td>
<td>9305</td>
</tr>
<tr>
<td>Ares V (LV 51.00.39)</td>
<td>10</td>
<td>~140,000</td>
<td>~70,000</td>
<td>~36,000</td>
<td>~55,600</td>
<td>~53,000</td>
</tr>
</tbody>
</table>
Fig. 3. Ares V launch vehicle stands 116.2 m tall with a Gross Liftoff Mass of 3700 mT. It consists of a central core stage with six RS-68 engines, two 5.5 segment solid rocket boosters, an Earth departure stage (EDS) with a J-2X engine, and a 10 m diameter payload fairing. Total payload capability is \( \sim 62.8 \) mT to Direct TLI and \( \sim 187.7 \) mT to LEO. Please note: These values are only for Ares V LV 51.00.48 and may not represent the latest design specifications.

Fig. 4. Ares V baseline shroud dimensions and payload mass capability. Please note: these values are only for Ares V LV 51.00.39 and may not represent the latest shroud dimensions and weights.

Table 4
Estimate Maximum Launch Loads for an Ares V (51.00.39).

<table>
<thead>
<tr>
<th>Maximum launch load</th>
<th>Steady state (g)</th>
<th>Dynamic (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial (flight and MECO)</td>
<td>4 ( \pm ) 1</td>
<td>( \pm ) 0.5</td>
</tr>
<tr>
<td>Lateral (wind load)</td>
<td>1.5 ( \pm ) 0.5</td>
<td>( \pm ) 0.5</td>
</tr>
</tbody>
</table>

The maximum payload mass which can be delivered to LEO as a function of altitude and inclination angle, as shown in Fig. 5, far exceeds any previous launch vehicle. For example, Ares V can deliver \( > 115,000 \) kg to the Hubble Space Telescope orbit of 590 km with an inclination angle of 28.5\(^\circ\). Or, it can deliver \( > 130,000 \) kg to the International Space Station which orbits from 360 to 440 km with an inclination angle of 51.6\(^\circ\). For this analysis, payload mass includes spacecraft, payload adapter and any mission specific hardware. The current configuration LV 51.00.48 is expected to be able to deliver \( \sim 40,000 \) kg more mass to LEO than configuration LV 51.00.39.

The maximum payload mass which can be delivered by LV 51.00.39 to various other orbits (Sun–Earth L2 (SE-L2), GEO, etc.) was analyzed assuming a direct insertion without gravity assist (Table 5). Of most interest to astrophysics missions is the ability to deliver 55,600 kg to SE-L2. (LV 51.00.48 is predicted to deliver 62–64 mT to SE-L2.) A key parameter in Table 5 is C3, which is defined as double the sum of the kinetic and potential energies per unit mass that the spacecraft must achieve to be on the correct trajectory to reach the target. A C3 of \( -0.7 \) km\(^2\)/s\(^2\) is required to transfer a given payload mass directly to the SE-L2 point. A larger payload mass could be delivered to SE-L2 using a lunar gravity assist, but would require several phasing orbits around the Earth before the lunar swing-by,
Fig. 5. Ares V payload mass (metric tons) to low Earth orbit depends on orbit altitude and inclination angle, the higher the orbit or greater the inclination angle, the less mass which can be launched. Data is for LV 51.00.39. Launch mass for LV 51.00.48 is expected to be $\sim 40,000$ kg more or $\sim 180,000$ kg to LEO.

Table 5

<table>
<thead>
<tr>
<th>Orbit Target Payload mass (kg)</th>
<th>Payload mass (kg)</th>
</tr>
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<tbody>
<tr>
<td>Sun–Earth L2 C3 of $-0.7 \text{ km}^2/\text{s}^2$ at $29.0^\circ$</td>
<td>55,600</td>
</tr>
<tr>
<td>GTO injection Transfer delta-V 2500 m/s 185 km at $27^\circ$</td>
<td>70,300</td>
</tr>
<tr>
<td>GEO Transfer Delta-V 4300 m/s 35,786 km Circular at $0^\circ$</td>
<td>36,200</td>
</tr>
<tr>
<td>Lunar transfer C3 of $-1.8 \text{ km}^2/\text{s}^2$ at $29.0^\circ$</td>
<td>56,800</td>
</tr>
</tbody>
</table>

posing the spacecraft to Earth’s radiation belts multiple times.

Maximum payload mass as a function of C3 for LV 51.00.39 was analyzed for both a base Ares V (core and upper stage) and for an Ares V with a 2-engine Centaur kick stage (Fig. 6). The Centaur & adapter mass is assumed to be 2910 kg. As shown in Fig. 7, previously unimagined payload masses can be delivered to the outer planets in reasonable durations. And lower mass payloads can be delivered even faster.

3. Potential science missions

The Ares V payload mass and volume capacities will be disruptive capabilities which can enable entirely new classes of astrophysics and planetary mission architectures.

For example, the large shroud diameter could accommodate an 8 m class monolithic primary mirror [12] or a 16 m JWST style telescope [13]. Alternative concepts have been proposed for a 24 m class segmented telescope [13]. Also, Ares V could launch an 8–12 m class X-ray observatory [14] or a large structurally connected stellar interferometer or a constellation of formation flying spacecraft. The potential applications are boundless. These next generation very large aperture 21st Century Space Observatories build on the Great Observatory legacy to offer previously unachievable science performance. They provide very high angular resolution, very high sensitivity, broad spectral coverage, and high performance stability. They offer the opportunity to expand humanity’s knowledge of the universe by imaging the event horizons of black holes consuming vast quantities of matter; studying dark energy and dark matter; observing galactic formation and evolution in the early universe; studying star and planetary system formation; searching for exo-solar terrestrial planets and eventually finding life on other planets.

Similarly, the Ares V offers significant advantages to the planetary science community. The increased payload volume enables the possibilities for large aeroshells or other structures or multiple element payloads as well as reducing complex deployments associ-
Fig. 6. Ares V alone or with a Centaur upper stage can accelerate previously unachievable masses (metric tones) to extremely large C3 Energy values, thus enabling and enhancing deep space planetary missions or missions outside of the ecliptic plane. Data is for LV 51.00.39.

Fig. 7. The very large C3 Energy values achievable by an Ares V with or without a Centaur upper stage significantly shorten the length of time needed to reach the outer planets with significant mission mass. Data is for LV 51.00.39.

ated with expansive spacecraft appendages [15]. The increased payload mass offers many advantages. It allows missions with more extensive and more complete instrumentation; a more capable spacecraft with greater power and higher performance telecommunications, and extra radiation or debris shielding. This extra mass capability enables extended duration in-situ observing campaigns of a wide range of potential target destinations.

Additionally, the Ares V C3 capacity adds a third advantage—the ability to get larger mass scientific payloads to distant locations faster—providing earlier science return and lower cruise time risk [15]. As shown in Fig. 7, Ares V (without a kick stage) can deliver close to 40,000 kg to Mars at a C3 of 10 km²/s². And with a Centaur kick stage, Ares V can launch approximately 20,000 kg to Jupiter in less than 3 years with a C3 of 80 km²/s². The C3 advantage of the Ares V
becomes even more dramatic for more distant planets. For example, approximately 13,000 kg would reach Saturn in approx. 6 years with a C3 of 106 km^2/s^2. Of course, some of this additional mass will be required for fuel to slow the spacecraft to orbit the destination. Or, maybe the mission will take advantage of the available launch volume to employ a large aero-capture shell.

Finally, the Ares V mass capability allows the ability to carry fuel sufficient to enable meaningful sample return missions. Such a capability is estimated to be able to return to Earth approximately 50 kg of Martian surface samples from two different sites [15]. And it is estimated that a direct return to Earth of a Titan or Enceladus atmospheric/plume sample could be accomplished in approximately 10 years as compared to 18–25 years for a Delta-IVH [15].

4. Programmatic advantages

Almost as important as the Ares V payload mass and volume capabilities are to increasing science return, they are also important for their potential to reduce cost and performance risk. The Ares V enables an entirely new paradigm in mission concept design—simplicity.

According to David Beardon [16,17], there is a direct correlation between mission payload complexity and mission cost as well as mission cost and schedule growth. And, the greatest predictor of mission success is technology maturity. The reason for this correlation is because the only way to achieve increasingly demanding performance requirements in a mass and volume constrained launch vehicle is to design increasingly complex mission payload architectures. Consider for example how JWST has segmented and folded a 6.5 m telescope to fit inside a 4.5 m fairing. Then consider how much simpler it would be to package a monolithic 8 m class telescope into a 10 m fairing.

This cost versus complexity relationship can be seen in Fig. 8 which plots actual mission development cost as a function of the Complexity Index developed by Dr. Beardon. The complexity index is determined by comparing mission parameters versus 150 satellite missions contained in the Aerospace Corporation Complexity Based Risk Assessment (CoBRA) database [16,17]. This cost versus complexity relationship is also evident in the NASA Advanced Mission Cost Model [18] (Fig. 9) which is typically used to justify (possibly incorrectly) that mass is the dominant mission cost driver. A closer look at the model indicates that difficulty level may be a larger cost driver than mass. To illustrate this relationship, the authors added low and very low difficulty level curves and extending the mass to 60,000 kg. For a detailed discussion of the mission payload complexity index as well as a full explanation of Fig. 8, the author recommends for readers to consult Refs. [16,17].

Given the available mass and volume capacity of the Ares V, designers can use simpler more-mature (and massive) technologies or higher design rule safety factors to eliminate complexity, to lower cost and to lower risk. By using mature technology, projects will save money on sub-system acquisition as well as engineering labor and management overhead. For example, using standard cost estimating models, a savings of $100 M in
Cost = $2.25B \times (\text{Mass/10000 kg})^{0.654} \times (1.555^{\text{Difficulty Level}}) \times (N^{-0.406})$

Very High (2)
High (1)
Average (0)
Low (-1)
Very Low (-2)

$0 \quad 2,000 \quad 4,000 \quad 6,000 \quad 8,000 \quad 10,000 \quad 12,000 \quad 14,000 \quad 16,000 \quad 18,000$

Fig. 9. Ares V mass capability allows for lower cost missions by trading complexity for mass. The NASA Advanced Mission Cost Model [18] is typically used to justify (possibly incorrectly) that mass is the dominant mission cost driver. But a closer look indicates that Difficulty Level may be a larger cost driver than mass. This point can be illustrated by adding low and very low difficulty level curves and extending the mass to 60,000 kg.

component cost reduces total program cost from $300 to $500 M. Now, while the cost savings of eliminating mass constraint is difficult to quantify, anecdotal evidence on current programs suggests that early in a mass constrained mission, it may cost $100 K of design effort to eliminate 1 kg of mass and that once the design is mature, it can cost as much as $1 M to eliminate 1 kg of mass.

Of course, from the perspective of total life-cycle cost, total payload cost savings need to exceed the incremental cost of the Ares V launch vehicle. Fortunately, while these costs are not yet fully known, they are expected to compare favorably with current heavy lift launch vehicles.

5. Conclusion

NASA’s planned Ares V cargo launch vehicle’s payload mass, volume and C3 capabilities completely change the paradigm of future astrophysics and planetary space science mission architectures. Its ability to place 140,000–180,000 kg of payload into LEO and 55,000–64,000 kg of payload into Sun–Earth L2 inside of a 10 m diameter fairing enables entirely new generations of space telescopes. Its ability to accelerate 18,000 kg to C3 of 80 km/s² enables entirely new generations of outer planet probes and sample return missions. Furthermore, the Ares V enables a new paradigm in mission design—simplicity. By taking advantage of the Ares V’s payload mass and volume capacity, mission designers can use simple mature technology to eliminate complexity and reduce program cost and increase mission reliability as well as science return.

References


