59th International Astronautical Congress

IAC-08-A5.3.6

DOES THE NASA CONSTELLATION ARCHITECTURE OFFER OPPORTUNITIES TO ACHIEVE SPACE SCIENCE GOALS IN SPACE?

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ABSTRACT

Future space science missions developed to achieve the most ambitious goals are likely to be complex, large, publicly and professionally very important, and at the limit of affordability. Consequently, it may be valuable if such missions can be upgraded, repaired, and/or deployed in space, either with robots or with astronauts. In response to a Request for Information from the US National Research Council panel on *Science Opportunities Enabled by NASA's Constellation System*, we developed a concept for astronaut-based in-space servicing at the Earth-Moon $L_{1,2}$ locations that may be implemented by using elements of NASA's Constellation architecture. This libration point jobsite could be of great value for major heliospheric and astronomy missions operating at Earth-Sun Lagrange points. We explored five alternative servicing options that plausibly would be available within about a decade. We highlight one that we believe is both the least costly and most efficiently uses Constellation hardware that appears to be available by mid-next decade: the Ares I launch vehicle, Orion/Crew Exploration Vehicle, Centaur vehicle, and an airlock/servicing node developed for lunar surface operations. Our concept may be considered similar to the Apollo 8 mission: a valuable exercise before descent by astronauts to the lunar surface.

"It is dumb to launch complicated, expensive telescopes into space that cannot be serviced."
-- Michael Griffin, NASA Administrator (11 February 2008)

1. The Case for In-Space Servicing Meets New Opportunities

Infrastructure currently planned to return humans to the lunar surface can achieve additional major goals in free space that are, at present, not otherwise possible. This infrastructure can deliver humans to locations where their unsurpassed abilities would be available to upgrade, repair, augment, or maintain important and expensive space assets. Although future space robotics are being assessed in this context, it is unlikely on the timescale of the next few decades that robots will surpass humans in their ability to carry out such critical tasks in space. Thus, it is desirable to examine in some depth how NASA's new Constellation Program hardware, which represents the next generation space transportation architecture for the United States, might be used to provide this in-space servicing capability in the relatively near future.

In the following sections, we explore the role that servicing by astronauts could play in lowering risk and increasing science results for especially ambitious future space science missions. In all cases, these missions are large, complex, very capable, and very expensive. We have used a major space astronomy mission concept as a notional placeholder for our assessment. This is appropriate because, in many respects, our concept is comparable to that for ground-based telescopes and HST, which produced major astronomical results well beyond that permitted by their original instrument complement. Furthermore, the vast majority of high-priority space astronomy goals are better achieved in free space than on the lunar surface (Lester, Yorke, and Mather 2004).

In our opinion, it is short-sighted to develop very ambitious – and very expensive – science missions based in free space and *not* have the ability to upgrade, repair, or re-provision them, if that ability can be achieved in a cost-effective way. Moreover, we believe that NASA's Constellation architecture offers such potential capabilities in addition to its primary goals of ferrying humans to the ISS and, eventually, returning humans to the lunar surface.

In April, 2008 the panel on *Science Opportunities Enabled by NASA's Constellation System* of the National Research Council (NRC) released a Request for Information (RFI) on concepts for using the Constellation architecture to enable major science goals. This paper summarizes our team's response to that RFI: a concept to enable such goals through in-space servicing, beginning as soon as about the middle of the next decade. The ability to service spacecraft will increase science value and lower mission risk for an entire class of ambitious missions. Moreover, given the rapid advance of technology, especially in detectors, computing, and communication systems, in-space servicing will result in orders of magnitude increase in scientific return from an existing facility, as has been demonstrated regularly for almost two decades with the Hubble Space Telescope (HST). HST is a proven, hugely successful program in which astronaut servicing has been invaluable. It is a model for the future that we consider here. At the same time, it is essential that an in-depth and objective assessment of the costs of in-space servicing relative to the scientific gains be carried out.

We examine five concepts that use elements of the NASA's Constellation architecture as currently understood for astronaut-based servicing at what we consider to be exceptionally valuable venues within cis-lunar space. Our concepts Our goal was to identify the astronaut-based servicing strategy that will have the lowest cost, requires development of the smallest number of elements of the Constellation architecture, and is most likely to be available soon after deployment of the Ares I and Orion crew transport systems.

We consider in particular that part of the Constellation architecture that would be deployed around the middle of the next decade. We assess the viability of several options for travel to a priority location in cis-lunar space and remain there for up to about two weeks of operations using a minimum number of Constellation elements. For several reasons, which will be described below, we consider the Earth-Moon $L_{1,2}$ locations to be the most attractive site for broadly useful servicing.[1] After our downselect, we summarize other advantages of our preferred concept, in addition to relatively near-term availability: (1) building upon extensive HST and ISS experience with in-space operations; (2) providing opportunities for international contributions; (3) continuing with the type of experience with in-space operations that will be necessary well in advance of human expeditions beyond the Earth-Moon system.

[1] A note on designations: as discussed in Section 3 and in many published papers, the two semi-stable Earth-Moon libration points, L_1 and L_2, in opposite sides of the Moon along the Earth-Moon line, are extremely attractive sites for in-space operations. There are some differences in the dynamics and accessibility of the two locations. However, these differences are not critical for most of our discussion, so in this paper we will usually designate them jointly as Earth-Moon (E-M) $L_{1,2}$.

Additional concepts and early design work on adapting the Constellation architecture may be found in Stevens and King (2005), Moe *et al.* (2005), Lester, Friedman, and Lillie (2005), Lester, Budinoff, and Lillie (2007) and references therein. Farquhar et al. (2003) discussed in detail options for servicing major observatories at libration points, although proposed developing spaceflight hardware in addition to that which is planned by the Constellation Program.

2. An Historical Note

The concepts that we consider here follow the long tradition of science communities using hardware and infrastructure that was intended originally exclusively for human spaceflight (cf., Thronson *et al.* 2007). In the mid-1960's, the Apollo Applications Program considered a number of adaptations of the Apollo crew and service modules intended to achieve significant Earth, solar, and astronomical science goals taking advantage of astronauts on site (e.g. Cohen 1967). Some of these designs were subsequently adapted for the Skylab program. Again, in the early 1970's, the science and human spaceflight communities worked together on early designs of the Space Shuttle that significantly broadened its value to multiple communities, with demonstrated early success in rescuing, upgrading, and repairing a number of satellites that were not originally intended to be serviced.

There is not at present an applications program for the Constellation program similar to that which led to the science productivity of Shuttle-based servicing of HST or science missions on Skylab. Such an applications program could play a significant role in achieving the full science potential of NASA's future space transportation system.

We note that about a decade ago, then-NASA Administrator Daniel Goldin chartered the Decadal Planning Team (DPT), which was followed by the NASA Exploration Team (NExT). Over three years, in advance of the Exploration Architecture Systems Study (ESAS), these teams investigated in depth the options, alternatives, technology investments, costs, and impact on science and human spaceflight for an architecture based on a series of "stepping stone" jobsites, such as the libration points that we evaluated. This paper attempts to put some of those decade-old trade studies into the context of the new Constellation architecture. An extensive discussion of the DPT and NExT efforts is in preparation by NASA's History Office (Asner and Garber 2009, in preparation).

3. Scientific Goals Enabled by this Capability

We emphasize how an ambitious future program of NASA human spaceflight, directed toward a human return to the Moon, can enable major science goals. As has been repeatedly demonstrated with the Hubble Space Telescope, using human spaceflight infrastructure has made that facility arguably the single most important science tool ever developed, although at a significant cost. In developing our case, we will refer to the Single Aperture Far Infrared Mission (SAFIR), which, in many respects, can be used here as a strawman example of a large, high-value astronomy mission class (Lester et al. 2008). As for all current mission concepts, SAFIR is baselined as being unserviced. However, the servicing option that the Constellation architecture could provide offers such a mission an upgrade path that would include new instruments, with new technologies, thus providing an order of magnitude or more of added capability. Such a servicing option also offers enhanced mission success.

Major astronomy goals for the ~2020 timeframe are derived from NASA strategic plans and reasonable extrapolation of community (e.g. National Academy of Sciences Astronomy Decadal Survey) input. These include study of Earth-like extrasolar planets, the detailed mechanisms with which stars are formed, characterization of the formation of the first galaxies out of primordial clouds, and exploration of the physics of compact regions such as black holes and galactic nuclei. Each of these goals requires large structures, whether for large light-collecting apertures providing greater sensitivity (as for SAFIR), or interferometric truss structures, both of which offer high spatial resolution. Such telescopes will inevitably be very costly, and their long term science value will be, as for HST and ground-based telescopes, dramatically enhanced by the opportunity for eventual instrument upgrade and subsystem replacement. The technologies for both focal plane sensor format size and sensitivity are on a steep development trajectory. This is just as for large ground-based observatories in which the major investment is in the telescope itself, which retains most of its scientific value after obsolescence of the focal plane instrumentation As we will describe below, we can predict this obsolescence of the focal plane instrumentation with some confidence.

In addition to science upgrades, in-space operations will extend the useful lifetime of an observatory by providing for maintenance of subsystems that are understood to have finite lifetime, such as station-keeping propellants (which will be needed at libration points, as well as for orientation and pointing systems), solar panels, and power storage systems. Such operations would also allow mission-critical upgrades for obsolescent spacecraft subsystems, such as computer and communication systems. While astronaut servicing has its own inherent risks, the availability of servicing dramatically lowers risk of single-point failure in the observatory, which would end its life prematurely. Finally, implementing design features that make in-space servicing possible may reduce overall mission costs, even if servicing is never carried out: integration & test in the final stages of mission development is almost certainly far easier for modular systems and sub-systems.

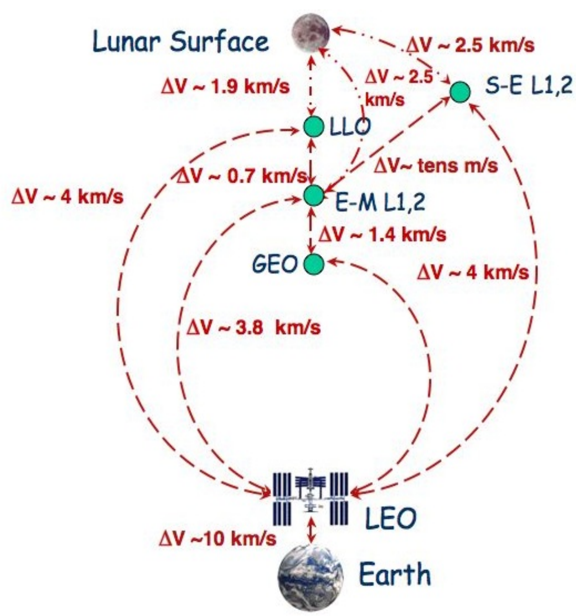

FIGURE 1: The Earth-Moon $L_{1,2}$ locations may be the most valuable jobsite in cis-lunar space to achieve major science goals. Shown here are approximate high-thrust ΔVs needed for movement among different locations in cis-lunar space. Travel between the preferred astronomy operations site at Earth-Sun $L_{1,2}$ and Earth-Moon $L_{1,2}$ jobsite reachable by using Constellation systems requires orders of magnitude less energy than that required to reach those locations directly from, for example, LEO.

A common characteristic of astronomical "flagship" missions, is operation at Sun-Earth L_2. This location, roughly four times the lunar distance in the anti-sunward direction, has enormous value for space astronomy owing to the low torques, readily manageable thermal environment, large available field of regard, uninterrupted line of communication to Earth and continuous solar power. The majority of future astronomy missions are, for these reasons, destined for this location. At this distance, visits by astronauts can be considered problematic, mainly because of weeks-long transit times, which increases radiation hazards and unexpected failure of major onboard systems. That is, it is difficult to justify long human voyages in space that are not absolutely necessary. Consequently, for the foreseeable future, visits beyond the Moon may not be easily achieved within NASA plans for returning humans to the lunar surface.

The possibility of servicing observatories by returning them to low Earth orbit (LEO) appears of little value, as it requires propulsive loads too large for the lightweight support structures of space telescopes, as well as exposing precision mirror coatings and materials to contaminants and debris from this increasingly polluted location. Therefore, servicing by humans or robots ideally requires a jobsite well beyond LEO, but not far beyond the Moon. This seems to us to be an obvious and natural role for Constellation system capabilities.

Of paramount importance in this context is the low-energy pathway between Sun-Earth $L_{1,2}$ and the more accessible Earth-Moon $L_{1,2}$ (see Figure 1). These latter locations are roughly 16% of the Earth-Moon distance on either side of the Moon on the Earth-Moon line. This pathway between the Sun-Earth and Earth-Moon libration points connects, at remarkably low propulsive cost, (1) the best astronomical observing site in cis-lunar space to (2) what may be, with the development of the Constellation architecture, a jobsite that is easily within the transportation capabilities of near-term elements of NASA's future human spaceflight architecture. We thus consider a servicing operation plan whereby the science facility makes a low delta-V (and somewhat leisurely) return from the Earth-Sun $L_{1,2}$ observing site to an Earth-Moon Lagrange point jobsite, where it is met by the astronauts and their servicing system.

Before we assess individual concepts, we note special engineering challenges that will need to be addressed with regard to such servicing efforts. For precision optical systems, a key challenge will be the fragility of the observatory, and the sensitivity of the performance to contamination, perhaps by propellants, waste dumps, or outgassing of a freshly launched Orion stack. In the case of an observatory that uses passive-cooling shields intensively, such as the Single-Aperture Far-Infrared (SAFIR) observatory, special care will be necessary to prevent freeze-out contamination, even at the Earth-Moon $L_{1,2}$, and damage to the observatory that could compromise performance. We believe these challenges can be mitigated by appropriate mission design and operations.

Servicing opportunities for large, high-value astronomical facilities provide far more than just mitigation of system risk. As we have learned with HST, a long-lived facility must have instrumentation that is responsive to new science questions and to the development of new technology. In astronomy, focal plane sensors are developing rapidly in both format size and per-pixel performance. The trajectory for that development is especially steep at infrared/sub-mm wavelengths. Very simply, the format size of astronomical detectors follows Moore's Law, such that every 10 years the number of pixels available to be put in the focal plane, and hence the amount of astronomical information available per unit observing time increases by a factor of 100 for a telescope that can be upgraded. This is shown in Figure 2 for visual, near-, mid-, and far-infrared detectors. This increase can be multiplied further by per-pixel performance increases, which in many parts of the spectrum are now far from theoretical limits. At least for UV and IR (such as SAFIR) missions, broadband imaging can be confusion limited, so that the pixel count is, in fact, a measure of target information obtained.

The impact of Moore's Law to astronomical science is multiplied, for example in the case of SAFIR's far-infrared detector needs, by the rapid improvement of per-pixel sensitivities. While technology roadmaps to achieve theoretical limits for far-infrared detector

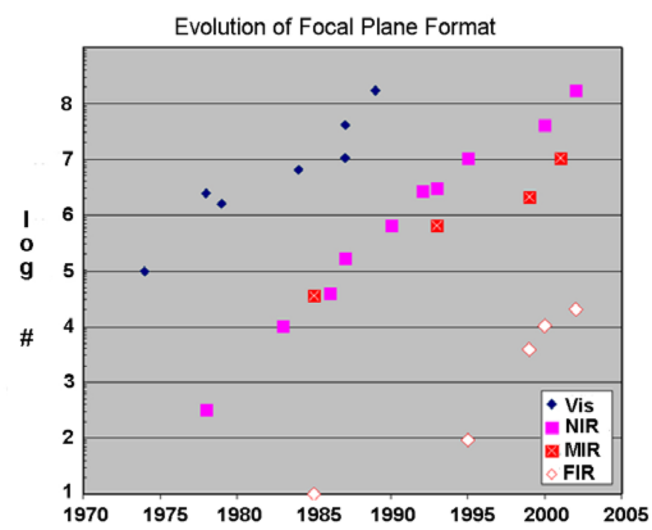

FIGURE 2: The remarkable growth in number of detector pixels demonstrates the value of servicing and focal place instrument replacement for those space astronomy missions that can be upgraded. Focal plane array size is a clear metric for technological advance that enhances science productivity in all astronomy missions.

sensitivity are available, we are presently one or two orders of magnitude away from achieving this ultimate performance. The HST servicing program achieved its striking scientific success while optical focal plane detectors were at precisely this phase of developmental evolution. Servicing and instrument replacement has been a hallmark of ground-based astronomy, in which technology upgrade is straightforward, and the large light-gathering power and pointing performance of even old telescopes can be continually improved, dramatically building on an original investment.

4. Five Basic Constellation Astronaut-Based Servicing Concepts

Here we describe five concepts that we assessed in response to the NRC RFI in April 2008 and identify the one that we believe makes use of the minimum – which also may be the least costly – Constellation architecture elements and which will also be available within about the next 10 years. As described in the previous section, we evaluate these under the requirement that the mission concept allows can reach the important Earth-Moon $L_{1,2}$ venue and to support astronaut extravehicular activity (EVA) at that location for at least two weeks. This would allow HST-like servicing scenarios.

Following the guidelines in the RFI, we limited our assessments to *only* elements of the Constellation architecture and simple derivatives. We consider both new hardware (Ares I, Ares V) and the Centaur upper stage (see data in Isakowitz 2004). This candidate upper stage is included in NASA's "Constellation Overview" provided to the NRC as an integral component in the suite of propulsion options in the Constellation spaceflight architecture. The essential system characteristic at this stage of assessment is use of a *minimum number* of early-development elements of the Constellation architecture that achieves sufficient velocity for departure from LEO to the Earth-Moon $L_{1,2}$. That is, about 3 km s^{-1} to reach the location, about 0.5 km s^{-1} for insertion into orbit, and an additional approximately 0.5 km s^{-1} propulsion requirement for station keeping, and return to Earth. Thus, we adopt 4.3 km s^{-1} from LEO as an approximate minimum requirement for a servicing mission to an Earth-Moon $L_{1,2}$ orbit. More sophisticated orbital calculations show that LEO departure velocities as low as 4.0 km s^{-1} may be possible in optimal situations (see below). Therefore, the first step in our assessment of different Constellation-based concepts was the simple requirement that the "stack" traveling to Earth-Moon $L_{1,2}$ was capable of a LEO-departure total velocity of a <u>minimum</u> 4

TABLE 1: Baseline Concept Parameters

Options	**A**	**B**	**C1**	**C2**	**D**
Configuration	Single Ares I	Dual Ares I (2x SM)	Dual Ares I (Centaur)	Dual Ares I (Centaur)	Ares V (EDS)
Human Servicing	Gemini-like	Gemini-like	Gemini-like	Via airlock	Via airlock
Ares-I Flights	1	2	2	2	0
Ares-V Flights	0	0	0	0	1
Propulsion Staging to E-M $L_{1,2}$ and return	SM	SM + SM	Centaur III+ SM	Centaur III + SM	EDS + SM
Total Delta V	**1.5 km s^{-1}***	**2.4 km s^{-1}***	**> 4 km s^{-1}**	**>4 km s^{-1}**	**>>4 km s^{-1}**
** configuration does not achieve minimal required Delta V of 4 km s^{-1}*					

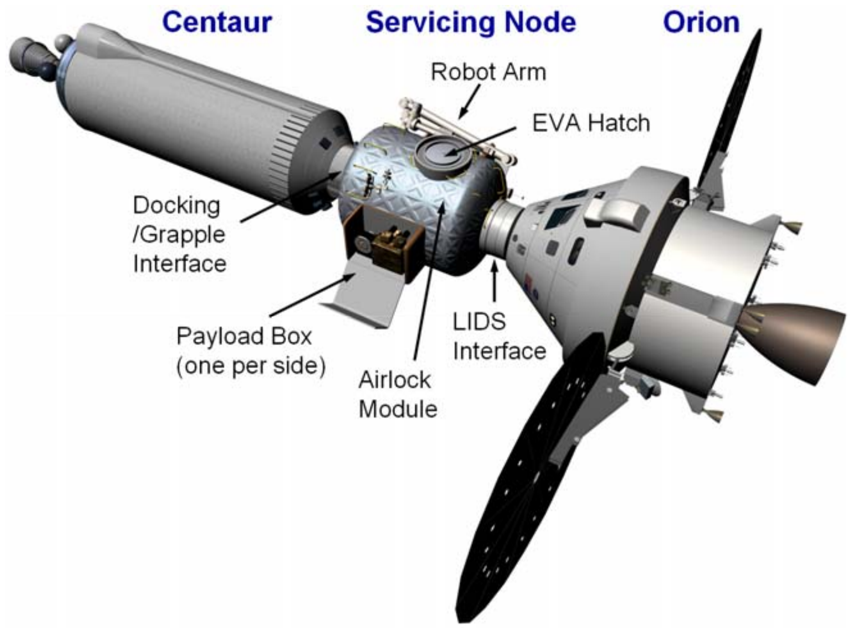

FIGURE 3: Our preferred concept that permits in-space servicing throughout the Earth-Moon system within about a decade. Basic parameters are listed in Table 1 as Option C2 and in Table 2. This figure shows the stack after Earth orbit rendezvous of the Orion (from one Ares I launch) with the Centaur and servicing node (from the second Ares I launch). The Centaur is ejected before rendezvous with the observatory at EM $L_{1,2}$.

km s^{-1} to be considered further

Calculated parameters, including velocities out of LEO, for the five options are presented in Table 1. The “Total Delta V” listed on the bottom line is the total that this configuration can achieve out of LEO, and can be compared directly with our 4 km s^{-1} minimum requirement.

A. Preferred Option [Columns C1 and C2 in Table 1; Figure 3]

We find that one concept (C) with two variants meets our minimum velocity requirement – one with (C2) and one without (C1) an airlock – with the fewest Constellation elements. Both options use a pair of back-to-back Ares I launches. Options A (a single Ares I launch) and B (two Ares I launches, with two standard service modules providing propulsion out of LEO) do not provide the necessary minimum propulsion to reach $L_{1,2}$, as indicated in red in the table. Option D, which assumes an Orion on a single Ares V vehicle, easily has the necessary propulsive power, but has other disadvantages within the context of the goals of our study. The options other than C will be briefly discussed below.

In both variants of option C, the first launch carries an Orion with a crew of two. (We made the rough estimate that the mass saving by a reduction in crew was offset by the necessity of including a pair of Shuttle-derived EVA suits.) The second vehicle carries a Centaur III. In one variant (C2, see Figure 3), the Ares I/Centaur launch includes a servicing node derived from the Altair lunar lander, which contains an airlock. Alternatively, variant C1 has no airlock, thus saving mass, and assumes cabin-depressurization (Gemini-like) EVA. Mass estimates of elements of these “stacks” are shown in Table 2 and variant C2 is shown in Figure 3. Figure 4 depicts one concept for servicing of SAFIR, where the Servicing Node had docked to the spacecraft on the sunward side of the observatory and the arm has grasped the telescope to bring it within reach of an astronaut EVA and/or a robot servicing system. Figure 5 shows a basic concept of operations for our C2 variant.

We point out that at present NASA is *not* planning to construct a second launch pad at Kennedy Space Center for Ares I. The Constellation program currently estimates a 45-day turn-around for Ares I launches, which would necessitate, for example, loitering of Orion at the International Space Station (ISS) until the

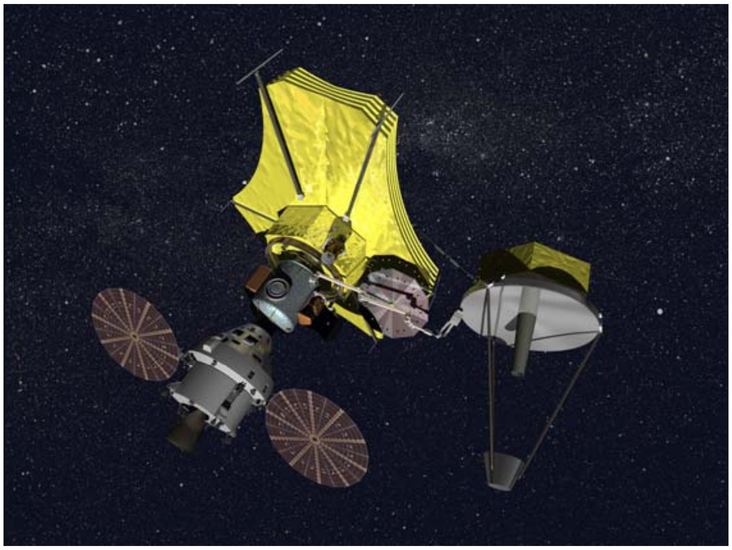

FIGURE 4: Concept variant C2 docked to the SAFIR observatory and grasping the optical system and instrument module in preparation for astronaut EVA and/or robotic servicing.

second launch of the Centaur may be possible, though an ISS orbit would require additional propulsion compared to a more equatorial LEO orbit. Neither this, nor loitering of the Centaur after launching first for that period (which would boil off a large fraction of its available cryogenic propellant) seems desirable, however. A viable alternative, according to the Ares V project office, is to launch the second Ares I more promptly from the pad being built for Ares V, which is intended to have such capability for Ares I as contingency back-up.

We first discuss variant C2, which includes an attached airlock. After Earth-orbit rendezvous, the Centaur serves as the transfer stage and provides the first 2.6 km s^{-1} of the 3.3 km s^{-1} necessary for transfer to Earth-Moon $L_{1,2}$, with the Orion service module (SM) providing the remainder, including orbital insertion, after Centaur staging. The Centaur thus serves the purpose of the Earth Departure Stage (EDS) on the Ares V, although available sooner and with a capability that is adequate for transporting only the Orion (and not the Altair lander) to the lunar vicinity. Although the current version of the Centaur is not human-rated, we note that such a similar transfer stage was baselined (Centaur-G) for the shuttle payload bay and its RL-10 engine has been identified as the descent engine for the human-carrying Altair lunar lander (data for the Centaur from Isakowitz 2004).

We consider it desirable, although not essential, for an airlock to be available for in-space astronaut servicing beyond LEO. Orion alone (our C1 variant) offers only limited EVA capabilities, rather similar to the Gemini spacecraft, which decompressed the entire spacecraft such that all occupants had to don bulky spacesuits. Moreover, the current design for the Orion Crew Module (CM) permits only three decompression/recompression cycles. Furthermore, the astronauts are presently limited to operating beyond their Orion spacecraft by a ~ 5 – 6 m umbilical. Finally, in our baseline C2 mission, the Altair-derived airlock itself offers additional operational volume, storage, and consumables.

However, the airlock has considerable mass, which otherwise might be available instead for additional payload in the C1 variant. We estimated the airlock mass based on that being designed for the Altair ascent stage, which has a calculated mass at this time of about 1000 kg. We consider it likely that it will be available well before humans return to the lunar surface. This airlock is the key component of the "servicing node", shown in Figure 3. Based on a simple engineering model, we have estimated the total airlock module to be 1700 kg.

Table 2: Adopted Masses of Elements of the Stack Shown in Figure 3.

Orion		**19700**	**kg**
	CM Gross	7900	kg
	SM Gross	11800	kg
	SM Propellant	8200	kg
Centaur		**22700**	**kg**
	Stage Propellant	20800	kg
Servicing Node		**2700+**	**kg**
	Airlock Module	1700	kg
	Robot Arm	1000	kg
	Mission Payload	<1000	kg
	Payload Accommodations	<400	kg
	Node Adapter/Grapple	<200	kg
	EVA Equipment	<500	kg
TOTAL		**47200**	**kg**

Table 2 summarizes the masses adopted or calculated for variant C2. The Orion and Centaur masses were used throughout Table 1. The masses for the Servicing Node are made up of two types. The airlock module and the robot arm are reasonable estimates at this early stage of assessment. The robot arm mass is derived from the arm developed for the unflown HST robotic servicing mission. If the "stack" shown in Figure 3 is flown (as opposed to option C1), a minimum additional mass of 2700 kg – airlock plus robot arm – must be included.

However, to accomplish useful tasks at the Earth-Moon $L_{1,2}$ jobsite, additional mass must be carried along: (1) Mission Payload (e.g., new instruments and replacement sub-systems); (2) Payload

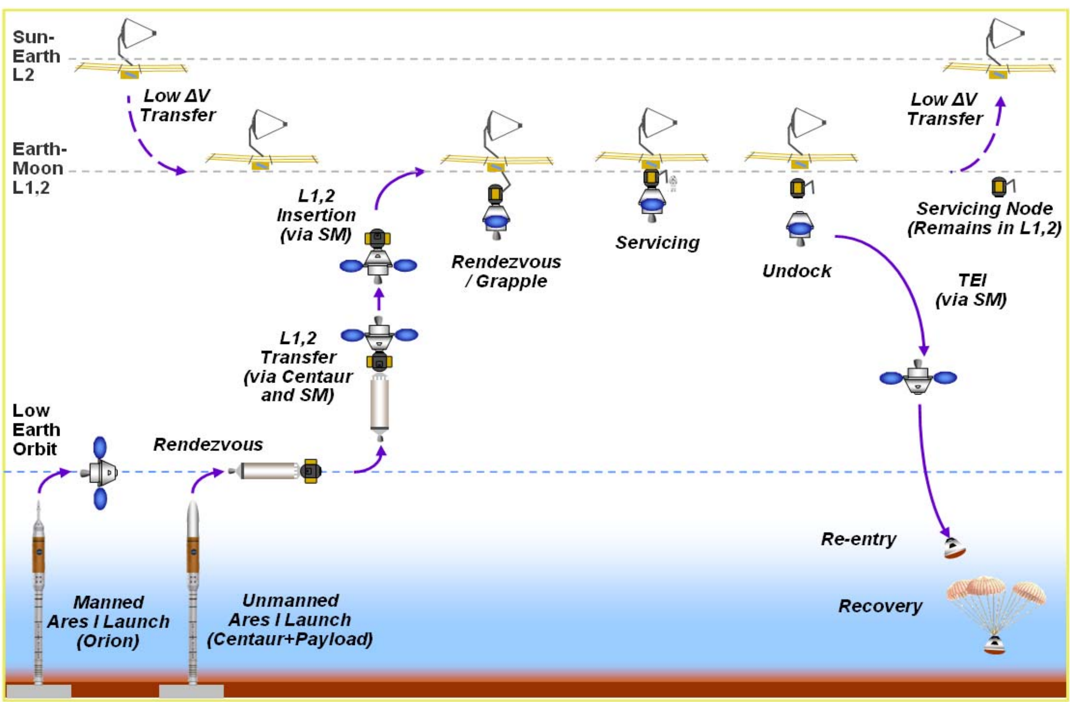

FIGURE 5: A chart of the concept of operations for our preferred option C2. The facility to be serviced, in this case an astronomical observatory, returns via low-energy (i.e.,Δ V) transfer from Earth-Sun L_2 to the Earth-Moon L_1 or L_2 location, where it is met by the Orion coupled to the Servicing Node module, the latter which features an airlock. This human transport system can remain on site for 2 weeks. Upon completion of the servicing mission, the Orion Crew Module returns to Earth and the Servicing Node may remain at one of the libration points for servicing use at later dates. If intended for reuse, the Servicing Node would be equipped with a sufficient communication and navigation systems, as well as nominal stationkeeping propulsion capabilities.

Accommodations (e.g., instrument mounts and brackets, storage boxes); (3) Node Grapple/Adapter for the robotic arm; and (4) EVA Equipment (e.g., tools). We included first-approximation upper limits to these elements in Table 2. However, these are merely notional and must be part of further design work. At this stage of analysis, we are satisfied by estimating that the Servicing Node in the "stack" in Figure 3 has a total lower mass limit of about 2700 kg, plus whatever additional mass is necessary if useful work is to be done at the jobsite. As Table 2 shows, if the Servicing Node is instead <u>not</u> part of the mission (i.e., variant C1), a significant additional total payload mass becomes available.

With a concept and two variants that appear to achieve the minimum requirements adopted for this study, the next step in our analysis was a much more detailed orbital analysis in which we treated the Servicing Node mass as a free parameter (next section). That is, we have good estimates for the mass of every other element in Figure 3. With the propulsion known for the Centaur III and Orion Service Module (SM), we can then calculate the total payload mass – including the Servicing Node for C2 – that can be carried via different routes to the Earth-Moon $L_{1,2}$ locations. Obviously, our estimate for this mass (above; Table 2) requires that this <u>calculated</u> mass be greater than about 2700 kg for a viable option C2.

This available additional payload mass available for other purposes in option C1 may be desirable for some missions. We regard this no-airlock option as possible, but not optimal for more complex in-space servicing missions. It might, however, be suitable for the most near-term astronaut missions out of LEO since it would not presume development of any more than a basic Ares I and Orion systems.

B. Two Basic Concepts with Insufficient Propulsion [Options A & B in Table 1]

Our assessments were strongly motivated to seek the minimum Constellation-based architecture capable of carrying two astronauts to the Earth-Moon libration orbit target location. We began by investigating a pair of superficially attractive concepts: a single Ares I/Orion launch *directly* to Earth-Moon $L_{1,2}$ with a CM lightweighted to carry a crew of two and using the SM as the sole propulsion system. option A in Table 1 was found to supply insufficient propulsion by a large factor.

We next investigated a *pair* of Ares I/Orion launches (option B), which would dock nose-to-nose in LEO and the pair of SMs would supply the propulsion. We investigated this particular option, as a second Orion CM would offer significant additional working volume, available consumables, and could serve as an airlock for EVAs. A crew of two was in the first launch and the second launch carried no astronauts, but even with plausible lightweighting of the second CM, the pair of SMs provided insufficient propulsion to reach the target location. Indeed, even *without* the second Orion CM – that is, *no* additional mass attached to the second SM – the pair of SMs were not capable of reaching the target location with the lightweighted CM.

C. Ares V: A Single-Launch Servicing Strategy for Cis-Lunar Space [option D in Table 1]

NASA plans to develop the Ares V heavy-lift vehicle over the coming decade to support a return to the lunar surface by ~2020. Current requirements for this vehicle are specifically not to preclude human rating, and it is our understanding that such human rating of Ares V is considered a useful long-range goal by NASA. The Earth Departure Stage (EDS) and solid rocket boosters (SRBs) will already be human-rated, and, as with the Centaur, the EDS uses an RL-10 which, as noted above, is already baselined for the astronaut-carrying Altair lunar descent module. In view of this, we considered the option to use Ares V to launch an Orion with an airlock, atop a Constellation EDS, which is also intended to be deployed late next decade.

Ares V is so powerful that it would easily meet the basic goals that we have established for our study: human EVA operations at Earth-Moon $L_{1,2}$. Furthermore, this arrangement meets our needs in a single launch. Indeed, our analysis shows that there is very large available payload mass, which could be used to carry, for example, additional facilities, infrastructure, science missions, and so on. However, we did not identify this option as a *preferred* concept, as (1)

TABLE 4

Calculated Total Velocities and Payload/Servicing Node Masses for Concepts C1 and C2: Insertion into Earth-Moon L1 and L2

	DV (m/s)	DV (m/s)	DV (m/s)	DV (m/s)	DV (m/s)	DV (m/s)
	Direct Injection	Direct Injection	Direct Injection	Direct Injection	Lunar assist	Lunar assist
	Large L1	Small L1	Large L2	Small L2	Large L1	Large L2
Transfer Injection	**3200**	**3100**	**3200**	**3200**	**3200**	**3200**
(C3)	**(-2.2)**	**(-2.3)**	**(-1.6)**	**(-1.6)**	**(-1.6)**	**(-1.6)**
Libration Injection	**440**	**620**	**880**	**1000**	**200**	**400**
Deterministic	**30**	**30**	**30**	**30**	**30**	**30**
Stationkeeping (per year)	**60**	**60**	**60**	**60**	**60**	**60**
Libration Departure	**430**	**620**	**750**	**1000**	**300**	**500**
Earth Transfer trimming	**50**	**50**	**50**	**50**	**50**	**50**
DV Tranfer+inj+depart	**4070**	**4340**	**4830**	**5200**	**3700**	**4100**
TOTAL DV	**4210**	**4480**	**4970**	**5340**	**3840**	**4240**
Payload (C1) or Servicing Node (C2) (kg)	**2800**	**350**	**(-2300)**	**(-4500)**	**5300**	**2500**
Durations (days):						
L1 or L2 Period	12	11	14	14	14	12
Transfer	4.4	4.4	6.4	6.5	16	12

Green boxes identify lower DVs
Assumptions:
LEO departure at 28.5 deg and 185 km circular orbit
Large L1/L2 is y amp ~ 60,000 km
Small L1/L2 is y amp ~ 15,000 km
Earth entry, no orbit
Lissajous Orbit / Lyaponav

it is almost certain to be a less economical approach, as the Ares V system is far more capable than we require to achieve the goals our study, and (2) it will not be the first available among the options that we considered and depends upon successful development of the full complement of Constellation infrastructure, specifically a human-rated Ares V and the EDS.

5. Optimized Payload Masses to Earth-Moon $L_{1,2}$: More Sophisticated Orbital Dynamics

The basic preferred concept (Figure 3, option C2) for astronaut-based servicing within about a decade at Earth-Moon $L_{1,2}$ appears promising within the limitations of our preliminary assessment (previous section). In this section, we consider different trajectories between LEO and the two Earth-Moon libration points. In the following analysis, we treat the mass of the Servicing Node as a free parameter and seek trajectories to the libration points with the lowest required velocities, which would permit larger masses for the Servicing Node – or, in its place, additional payload (C1) – and associated equipment. As discussed for Table 2, we estimate a <u>minimum</u> mass for the Servicing Node of about 2700 kg. Of course, we would like to find plausible trajectories out of LEO – and return to Earth with the Orion crew module – that permits Servicing Node masses much greater than 2700 kg for the more capable C2.

The results of analyzing several trajectories are shown in Table 4 for six basic orbits. “Large L” and “Small L” refer to the size of the orbit around either of the libration points, $L_{1,2}$. Large orbits at these locations are well known to require less energy – a lower velocity – for injection into (and out of).

The calculated available payload mass must be greater than about 2700 kg – the mass for the Servicing Node – for variant C2. We find that the available payload mass using direct injection into a large obit around E-M L_1 is not much more than the minimum mass that we estimate for the Servicing Node alone (Column 1 in Table 2). At the level of this preliminary analysis, we estimate that this trajectory appears to permit only a Servicing Node-based mission with limited payload. However, the permitted Servicing Node mass is large enough that we consider it very worthwhile to pursue this concept with more sophisticated analysis, including the possibility of, for example, a more powerful transfer stage option than a Centaur III.

On the other hand, the detailed analysis shows that E-M L_1 and L_2 are not strictly equivalent. The velocities for direct insertion into and return from the E-M L_2 location are so large as to preclude significant Constellation-based operations at this location. Indeed, the calculated available payload/Servicing Node mass is <u>negative</u>, which means that the Orion vehicle would have to be lightweighted far more than seems plausible at this time to even make such a mission possible, even without the Servicing Node. Pending more detailed studies, it would appear that neither of the variants for concept C is viable for a Earth-Moon L_2 destination.

Finally, we examined the effect of using the Moon’s kinetic energy to reduce the velocity required of the system in Figure 3: a lunar swing-by and insertion into the large orbits around either the L_1 or L_2 location. The results in our table show that the additional velocity imparted to the “stack” is sufficient to permit a very significant increase in the allowed payload/Servicing Node mass. Of course, the penalty for swing-by orbits is an increased transfer time from LEO to the jobsite: about two weeks, rather than 3 – 4 days for direct injection. This may not be insurmountable, given the significant increase in calculated available mass, although all human spaceflight missions generally try to minimize the amount of time spent in space.

In summary, we have identified a basic concept to use a pair of Ares I launches, a Centaur transfer vehicle, and an Orion Crew Exploration Vehicle that would appear to be able to service, repair, and upgrade major scientific facilities at the Earth-Moon L_1 location by around the middle of the next decade. Given that the Ares I system – or its successors – are intended to be a key element in transporting humans to the International Space Station over the coming decade and to be part of the return of humans to the lunar surface, it is reasonable to assume that Ares I will be available for many years into the future.

We emphasize the preliminary nature of our work, produced in response to a specific Request for Information from the US National Research Council. Additional work on these topics, using different assumptions would be revealing.

6. Recommendations

The opportunities for large, expensive future science missions in cis-lunar space, particularly those placed there using the proposed Ares V heavy-lift launch vehicle, argue strongly for a strategy to service these missions, with robots and/or astronauts. Such a strategy may reduce overall mission cost and risk, as well as increase lifetime and productivity by making the already-expensive science mission responsive to ongoing technology developments. With respect to servicing of science missions by astronauts, which has been proven invaluable on HST, further work should evaluate the benefits – and an objective assessment of the costs – and recognize that the Constellation architecture provides a basis for such in-space activities in a way never before possible. In the longer term, such efforts could pave the way one day to actual in-space construction of large science facilities, transcending the size limits that will occur even with Ares V. Such a capability would build upon extensive in-space experience developed for the ISS and as part of the HST servicing program.

Following earlier pre-ESAS work by the Decade Planning and NASA Exploration Teams (Asner and Garber 2009, in preparation), we have presented a strategy that highlights the special value of Earth-Moon Lagrange points as servicing jobsites. A more detailed evaluation is called for, which should include the potential value of such a jobsite to a lunar surface exploration program. Finally, any future technology program should include enabling capabilities important to our concepts: robot systems, large optics systems, computing and IT, power generation and storage, communication systems, and in-space human systems (e.g., EVA suits, life support).

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