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# The Opportunity in Commercial Approaches for Future NASA Deep Space Exploration Elements

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**In 2011, NASA released a report assessing the market for commercial crew and cargo services to low Earth orbit (LEO). The report stated that NASA had spent a few hundred million dollars in the Commercial Orbital Transportation Services *(*COTS) program on the portion related to the development of the Falcon 9 launch vehicle. Yet a NASA cost model predicted the cost would have been significantly more with a non-commercial cost-plus contracting approach.[1] By 2016 a NASA request for information[2] stated it must "maximize the efficiency and sustainability of the Exploration Systems development programs", as "critical to free resources for re-investment…such as other required deep space exploration capabilities."**

**This work joins the previous two events, showing the potential for commercial, public private partnerships, modeled on programs like COTS, to reduce the cost to NASA significantly for "…other required deep space exploration capabilities." These other capabilities include landers, stages and more. We mature the concept of "costed baseball cards",[3] adding cost estimates to NASA's space systems "baseball cards."[4,5]**

**We show some potential costs, including analysis, the basis of estimates, data sources and caveats to address a critical question – *based on initial assessment, are significant agency resources justified for more detailed analysis and due diligence to understand and invest in public private partnerships for human deep space exploration systems?* The cost analysis spans commercial to cost-plus contracting approaches, for smaller elements vs. larger, with some variation for lunar or Mars.**

**By extension, we delve briefly into the potentially much broader significance of the individual cost estimates if taken together as a NASA investment portfolio where public private partnership are stitched together for deep space exploration. How might multiple improvements in individual systems add up to NASA human deep space exploration achievements, realistically, affordably, sustainably, in a relevant timeframe?**

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https://science.ksc.nasa.gov/shuttle/nexgen/EZBio.htm

## Nomenclature

| | | |
|---|---|---|
| *CCP* | = | Commercial Crew Program |
| *CCSC* | = | Collaborations for Commercial Space Capabilities |
| *COTS* | = | Commercial Orbital Transportation Services |
| *C&N* | = | Communications and Navigation |
| *CRS* | = | Commercial Resupply Services |
| *CSM* | = | Command/Service Module |
| *DDT&E* | = | Design, Development, Test and Evaluation |
| *EUS* | = | Exploration Upper Stage |
| *FAA* | = | Federal Aviation Administration |
| *ISRU* | = | In-Situ Resource Utilization |
| *ISS* | = | International Space Station |
| *KSC* | = | Kennedy Space Center |
| *LCOTS* | = | Lunar Commercial Orbital Transfer Services |
| *LEO* | = | Low Earth Orbit |
| *LH* | = | Liquid Hydrogen |
| *LM* | = | Lunar Module |
| *LSP* | = | Launch Services Program |
| *NAFCOM* | = | NASA Air Force Cost Model |
| *OTA* | = | Other Transaction Authority |
| *PPP* | = | Public Private Partnerships |
| *ROM* | = | Rough Order of Magnitude |
| *RP* | = | Rocket Propellant |
| *SLS* | = | Space Launch System |

## I. Introduction

Disentangling the affordability of human deep space exploration overall from specific projects like lunar or Mars landers is critical to understanding how NASA might achieve its space exploration goals. This observation is not entirely new. In NASA's Constellation program to return to the moon, congressional review noted that most of the "development risk lies beyond 2012 timeframe, when NASA begins work on the various craft needed to support a lunar mission."[6] Looked at from this pure budget perspective, the 2010 White House budget did not propose to cancel the Constellation program per se. As confirmed over time, the budget proposed *not to add new items to the NASA budget for capabilities beyond Earth orbit*. Specifically, the budget would not fund a lunar lander just as this item needed initial funds to make the overall program goal real - *human expeditions to the lunar surface*.[7] Predictably, as the 2009 Human Space Flight committee concluded - "exploration really doesn't look viable under the [fiscal year 2010] budget guidance."[8]

Vague notions about what is affordable in space exploration mix with specific capabilities for going beyond low Earth orbit, things like landers. This may seem a mere nit, some inside baseball about budgets, the Moon and Mars. Actually, this connection between general goals and specific space systems like landers is critical, touching on the broader dilemma where it's been observed that "NASA's human spaceflight budget has been able to afford one or two modestly-sized programs at a time."[9] Nonetheless, human deep space exploration requires *many* new and *major* project elements (perhaps as many as 11)[10] that together go well beyond a single new program or two, and well beyond "modestly-sized". Each of these new elements is a new layer of cost to add to NASA's budget. It's also been observed that when exploration approaches depend on adding ever more layers of cost to NASA's budget that even adding money just delays re-entering the same trap. Then "you are right back where you started, the budget crashes, you can't afford to build the new thing without cancelling the old thing."[11] A related version of this rule of thumb occurs with expectations, where "Programs that depend upon continually increasing budgets, however modest the required increases, have historically failed to meet the expectations of stakeholders."[12]

What are the projects that must fit inside existing budgets if space exploration by NASA beyond Earth orbit is to happen? New elements of a program for going beyond Earth orbit, to the Moon, Mars or elsewhere include -

- **Exploratory probes**, instruments, equipment
- **Deep space communications** infrastructure, satellites, network
- **In-space stages**, to leave low Earth orbit and to return, propulsion in space
- **Landers** to deliver crew and cargo to a surface to explore, including ascent and return capability
- **Habitation** for crew *in space*
- **Habitation** for crew *at the surface* destination, including **power** and capabilities for **processing native resources**
- **And much more** - from **spacesuits** for surface operations, to **rovers** to move around at the destination, to **other spacecraft** designed specifically for operations in space, for crew and/or cargo, to **propellant depots** and related elements like **refillable stages** and propellant **tankers**

A natural segue from these observations is to reach for the NASA budget, to see if something has changed, if the facts on the ground are now different, once again trying to cancel an "old thing" to get started on a "new thing". Such a solution (strategy or plan) has the problems already observed. Qualitatively, all these observations about cost risks tomorrow, awaiting canceling one thing to do something new, and the inability to piece together enough new things soon enough to matter anyway, are all versions of an over-extended supply line dilemma. That is, *it's not possible to forge ahead if doing so depends on dismantling what came before that makes forging ahead possible.*

More specifically, a path here is to point to the ISS and its inevitable end. More specifically as well, there are systemic factors why a strategy/plan that depends on ending one major space flight program to fund another one, or multiple other deep space exploration elements, easily runs aground -

1) **Cost inflation**, NASA's loss of purchase power over time
2) **The cost to low Earth orbit**, that cost of any chosen way of launching deep space exploration elements, remembering that as we add new exploration elements we also add the launch costs for these elements
   - Any new payloads cost more payload money and more launch money
   - S*aving funds by launching less often or less tonnage, leads to (4)*
3) **The cumulative cost of deep space exploration elements** *potentially* adding up to more funding than freed up by the end of the ISS program; adding up to more than another modestly sized program alongside the other modestly sized program that launches elements as far as Earth orbit
   - As time is money, this relates to -
4) **Irrelevance**, as when the tangible exploration milestones that might result are pushed so far away as to foster disregard from most stakeholders; tangible milestones like crew on another world, a permanent crew presence, a self-sustaining human presence elsewhere in the solar system or human settlement
   - *Instead of* reaching *for the stars, we reach for irrelevance*

Cost inflation is a particularly thorny subject, with numerous studies attempting to get NASA budgets to add-up to exploration at some point in the future by glossing over inflation, by *assuming* what has not happened historically, that NASA budgets will keep up with cost inflation[13,14,15] - starting tomorrow. Usually this broad assumption also goes along with a specific low rate of inflation, 2.5% a year, a value close to inflation in the general economy.[16] The assumption treats aerospace like non-aerospace goods and services, a poor assumption. Worse, this is actually two poor assumptions masking as one. This assumption about the long-term rate for NASA budget increases is also about NASA's complex aerospace projects behaving, increasing in costs year over year at no more than the same low rate. By relation, there is an unusual conflation between cost inflation for aerospace projects and a growth index provided for planning future budgets.[17] Planning confuses estimating the rate at which a projects costs may rise over time, something that would be amenable to historical analysis specific to that field, with a rate that's simply dictated as tolerable for developing budget outlooks. Cost inflation for large-scale projects is, if anything, "systematically under-funded,"[18] "inappropriate,"[19] misunderstood, or likely much higher[20] than any inflation indices dictated for planning.

If there is a stronger assumption here, useful for planning purposes, versus a weak assumption that is wishful, and more than likely to prove false, it is to assume NASA's future budgets simply follow past experience. Since 2003, NASA's budget has risen on average 1.81% per year (at times more, at times less). This is an overall decline of at least 11% in NASA's purchasing power since 2003 using the official NASA Inflation Indices.

Also entangled are the cost to low Earth orbit and the cumulative cost of deep space exploration elements. A given amount of funds could be available after the end of the ISS, but any deep space exploration elements must first pass by low Earth orbit. If the costs to low Earth orbit also put a lien on the funds made available post-ISS, then there is that much less for the payloads, the deep space exploration elements. The difficulty in getting NASA's budget numbers to add up to human deep space exploration is easily apparent, even after the end of ISS. Figure 1, the Baseline Scenario, exemplifies this difficulty.

However, dissecting this problem, assuming NASA overcomes systemic factors 1 (loss of purchase power) and 2 (costs to low Earth orbit), perhaps going down alternate paths and scenarios,[21] still leaves factors 3 and 4 – the focus of the work here. To know the cumulative cost of deep space exploration elements we need to know what the specific layers of cost for specific deep space elements might be. As importantly, while tempting and mathematically possible, we are looking to reduce costs sufficiently to avoid having to spread costs over very long timeframes, avoiding problem 4 – irrelevance. This leads to the question –

*Are there public-private partnership paths that <u>significantly</u> reduce the cost of deep space exploration elements to NASA while achieving space exploration milestones <u>much sooner</u> rather than later?*

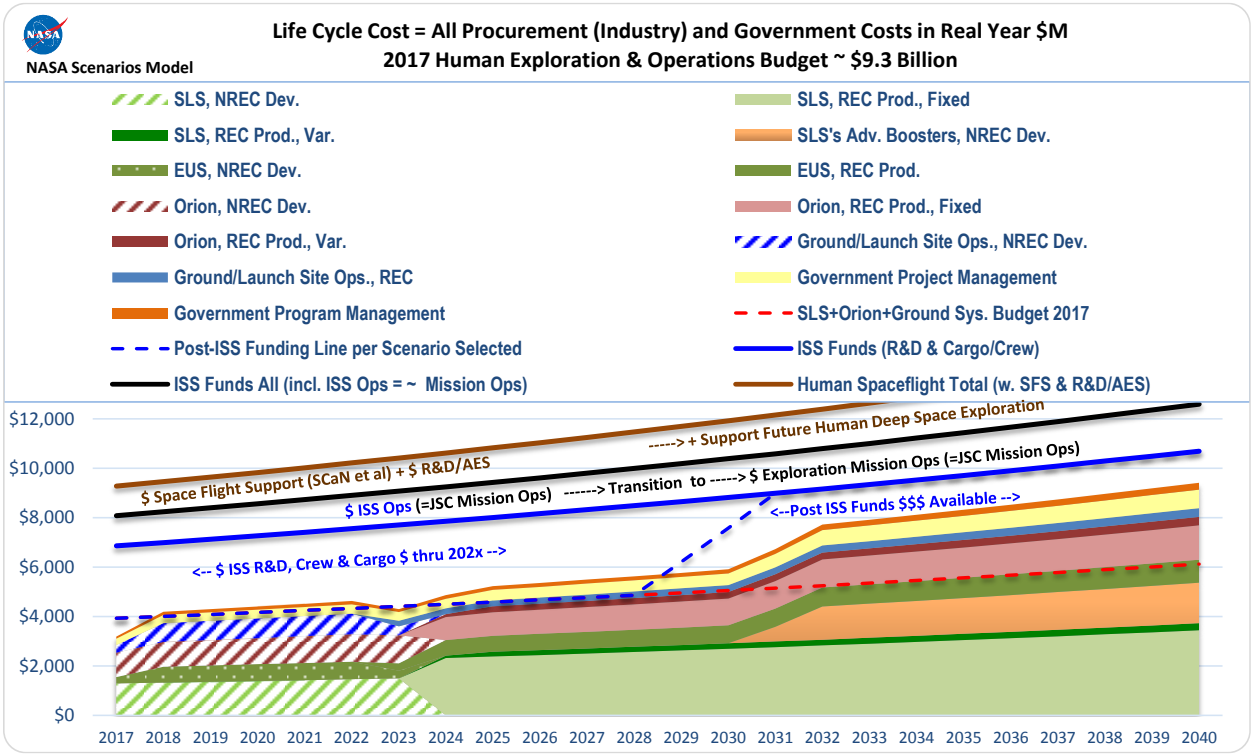


**Figure 1. NASA's Baseline Scenario.**[22] Even after the ISS ends, even if all its funding were then available for other projects, estimates show that money for deep space exploration elements may never appear. Immediate liens are placed against all the new available post-ISS funds by the production and operation of SLS twice a year and Orion once a year, with likely fixes, deferred development work and increasing the payload capability to 130t. Along with decreasing purchase power over time, the Baseline Scenario is a path to very few dollars in the 2020's and 2030's for deep space exploration elements like landers or habitats, even once ISS ends, simply from wanting to fly or upgrade the launch system developed to emplace these payloads. As already observed, delaying or not funding an Advanced Booster, or flying less often, simply worsens systemic factor #4, irrelevance, by stretching things out too far.

## II. An Alternative

In April 2011, NASA released a report assessing the market for commercial crew and cargo services to low Earth orbit (LEO). The last page of the report stated that NASA had spent a few hundred million dollars in the Commercial Orbital Transportation Services (COTS) program on the portion related to the development of the Falcon 9 launch vehicle. Yet the cost model traditionally used by NASA predicted the launcher's cost would have been a few billion dollars. The report added - "It is difficult to determine exactly why the actual cost was so dramatically lower than the NAFCOM predictions."[23] NASA later stated - "reducing the total workforce; number of management layers and infrastructure can substantially reduce DDT&E costs when compared to traditional NASA environment/culture."[24]

As importantly, the COTS program raised the bar for spacecraft with the Orbital ATK Cygnus and the SpaceX Dragon cargo spacecraft. The COTS program would have a recurring element too, the pricing on each mission under the CRS contracts. This pricing includes a launch vehicle, a spacecraft to carry the cargo NASA provides, and related operations in space through delivery of goods to the ISS. In 2010, NASA took a similar approach to develop a new capability to get US crew to the ISS from the US, the Commercial Crew Program (CCP). A rigorous review of the cost data for these programs demonstrated they offer significant cost reductions to NASA from development through launch as well as benefits for sustainability and other metrics.[25] With this in mind, is there reason to believe that deep space exploration elements like landers, stages or habitats could also benefit from this approach?

### A. Commercial – Beyond LEO

Inevitably, concerns about the maturity of potential company capabilities will arise when considering adding commercial elements to *deep space* exploration plans. Formally, there is no reason to assume an arbitrary point in space beyond which only traditional business-as-usual and cost-plus contracts need apply. Advocates in this area have said - "the artificial boundary being discussed in Washington makes no sense".[26] A compelling reason to avoid an artificial line in the sand, assuming what can or cannot be commercial in a deep space exploration architecture, or that commercial capabilities only go as far as LEO, is that it costs very little to understand potential industry capabilities beyond LEO. Similarly, if it is "sticker shock"[27] that is keeping deep space elements from being funded at all, it's reasonable to analyze possibilities that might avoid sticker shock.

NASA found itself in a similar situation in the 1980's, wanting to start a new thing but already having its plate full. The Space Shuttle was operational yet NASA was struggling to fund its next major program, a space station. Between announcing plans for a space station in 1984 and a first construction launch 14 years later, there was SpaceHab, a commercially developed module for scientific research carried inside the Space Shuttle. While NASA space flight was experiencing the same generation long[b] difficulty of budgeting two major programs at the same time, a transportation system's operation and a space station's development and construction, a commercial path appeared with significant affordability advantages. The commercial SpaceHab in the late 1980s also showed the promise of a commercial acquisition approach, radically reducing costs over traditional contracting. A Price Waterhouse analysis stated that a commercial approach offered significant cost savings to NASA, with a billion dollar cost of ownership versus a $159M cost of a lease.[28] NASA did something commercial in SpaceHab, sooner rather than later.

More recently, and to the point about commercial deep space capabilities, in 2010 NASA favorably assessed commercial options for deep space communications. NASA's Space Communications and Navigation (SCaN) program manages ground stations for the deep space network, a near Earth network and a space network constellation of geosynchronous satellites. This assessment included responses from industry, an independent market assessment, and a review of possible missions over the next 15 to 20 years. Subsequent work looked at the possibility of such a commercial arrangement being structured as a utility, where a "Power & Relay Utility consortium could be a profitable adjunct to developing the Moon."[29] This 2010 assessment concluded –

> *"…a commercial approach to providing lunar C&N* [communications and navigation] *services is feasible – technically, economically, and programmatically[30]."*
>
> *"It would be in the interest of NASA to foster growth of the commercial industry and to consider commercial partnerships to reduce lunar development and operations costs.[31]"*

[b] Over a generation, 27 years – as the time from 1984, the announcement of Space Station Freedom in President Reagans State of the Union Address, and 2011 when the ISS was completed.

Similarly, in 2015-16 NASA personnel assessed a Lunar exploration program structured around commercial services.[32,33] The Lunar Commercial Orbital Transfer Services (LCOTS) envisioned "cis-lunar capabilities to include autonomous lunar landings, robotic prospecting for resources, extraction or mining of lunar resources, drilling for water beneath the surface and ISRU [in-situ resource utilization] production of propellants, such as, LOX and LH2". A maturity assessment of candidate industry capabilities showed these were high in some areas and low in others, before any initial investment. The maturity assessment covered capability, number of companies, market, return on investment and risk reduction for Mars missions. Already promising capabilities would improve even further with relatively small investments.

Industry wise, no wall at LEO appears to be constraining actual projects or plans. In 2014, NASA competitively awarded Collaborations for Commercial Space Capabilities (CCSC) Space Act Agreements to four firms, agreeing to provide them with NASA's technical insight and assistance on a no-exchange-of-funds basis. One of these agreements was with SpaceX developing a Mars cargo transportation system "Red Dragon".[34] Originally, SpaceX worked with NASA Ames Research Center (ARC) in 2011 on the basis that a crew Dragon developed for transport to the International Space Station (ISS) and capable of a land landing back on Earth might be able to land elsewhere, like on Mars. Similarly, Blue Origin has proposed lunar landers delivering as much as 10,000 lb. of cargo to support a lunar outpost. Blue Origin's Jeff Bezos sees this as a necessary step for "cost-effective delivery of mass to the surface of the Moon…any credible first lunar settlement will require that capability."[35]

On the demand side of the equation, not the launch system provider but what goes atop the launcher, there are private sector initiatives that are not limited by any boundary at LEO. In 2016, Moon Express received Federal Aviation Administration (FAA) approval for landing a probe on the Moon.[36] Working with the FAA, NASA and the US State Department, a payload review process allows Moon Express to go beyond Earth's orbit.[37] Other companies like SpaceIL, Synergy Moon, TeamIndus and Hakuto are also competing for the $20M Google Lunar X-Prize to land a craft on the Moon.

Clearly, past and ongoing work indicates there is no arbitrary line at low Earth orbit that separates what NASA might do with public private partnerships vs. other more traditional means.

### B. Commercial – Beyond NASA

One factor used to characterize systems NASA might acquire on a commercial basis versus those to approach more traditionally (as with "cost-plus" contracting) is that of non-NASA business, or more generally non-government business. NASA would use a commercial contracting approach when it sees there could also be private sector customers for the system NASA wants. A company's business case for non-government customers, for creating or growing a market, informs NASA's assessment to acquire a system on a commercial basis or not. Though an extremely important factor, it is not a deciding factor, or a pass/fail gate. Many factors can make for a NASA acquisition being commercial. These factors lie along a spectrum, a matter of the degree to which an acquisition may be characterized as more commercial versus traditional. Assessing the maturity of a non-government market and partner business cases is just one factor in determining the appropriateness of a commercial / public private partnership for developing a new system. Partner technical capability, technical maturity, their willingness to assume cost risk, and the willingness to invest private funds should also inform the decision.

By way of real world examples, in the long list of items recently acquired by NASA commercially – Antares and Falcon 9 launch systems, the Cygnus cargo spacecraft[c], the Dragon cargo spacecraft[d], the Boeing Starliner-100 crew spacecraft, the SpaceX Dragon crew spacecraft, and all launcher services acquired by the NASA Launch Services Program (LSP) since 1990 – only the Falcon 9 and the Atlas launch systems have seen non-government customers to date. Of these two exceptions, only the Falcon 9 has seen significant non-government customers, exceeding government customers in 2016.

As well as the possibility of a non-government market, characteristics that make for a system acquisition being more or less commercial include -

- The degree to which NASA employs an "investor"[38] mindset
  - Especially for early contractual phases using Other Transaction Authority, NASA is making an *investment* not an *acquisition*

[c] Cygnus spacecraft have deployed a small number of cubesats for non-government customers.

[d] Red Dragon, a mission to Mars, though not an ISS mission, is not a SpaceX mission for a non-government customer outside of SpaceX.

- The degree to which NASA's requirements focus more on "what", and less on "how"
  - Innovation is not just allowed, it's encouraged when the focus is results, "what", versus activity, pre-existing process or prior ways of doing business and "how"
- The degree to which cost-risk is assumed by the private partner, not the government
  - Use of firm-fixed-price contracting,[39] where a cost over-run must be absorbed by the company partner, but alternately, where a cost improvement (reduction) means increased profits, or lower prices, market growth and yearly revenue growth
  - Fixed payments negotiated beforehand for achieving milestones; a healthier sharing of risk between the private sector partner and the government (versus cost-plus with all the cost risk remaining with the government)
- A maturation and risk buy down process involving numerous early partners
  - Delay's pre-mature decision making
- Eventually partnering with at least two providers in an operational / services phase
  - Competition is built in throughout, even in the operational phase
  - The government has redundancy in the acquisition of the service, reducing the risk inherent to a single system (downtime after a failure)
  - Each partner knows the government has a ready and operational alternative should their performance ever be problematic
  - Regular block purchases and/or exercise of contract options, seriously competing additional operational services, providing even more competition incentives for existing partners
- A commitment by NASA to buy future services
  - Reduces long term private capital investment risk
  - A commercial "service" as the requirement, as a result, versus the delivery of "hardware" to be owned by the government; firm-fixed-price for services
  - Limited termination provisions, encouraging private sector investment knowing the government cannot walk away as easily as in other contracts
- A small government office for acquisition, program/project management and related
  - 3 to 5% of the yearly funds under management[40]

Incentives to lower costs, while simultaneously increasing safety, reliability, and responsiveness are better aligned between the government and an industry partner in a commercial acquisition than in a traditional cost-plus acquisition. Even when non-government customers and market growth are not immediate incentives or reality, the path toward that end is encouraged and made possible by the assortment of other incentives.

Clearly, the viability of a non-NASA, non-government market is not the only factor qualifying a future system for a commercial acquisition approach by NASA or leading to significantly reduced costs to NASA.

### C. Commercial – Beyond Biases

Risk management is a central characteristic of a commercial acquisition approach. While a commercial acquisition passes more cost risk to the company partner than under a cost-plus contract, cost risk is inseparable from overall technical risk. Unforeseen technical problems, under-estimated difficulties and failures causing more time than originally planned create unexpected costs. Unexpected element costs affect a company's financial health, being responsible for cost overruns, which add to the overall risk NASA faces in successfully acquiring multiple capabilities for space exploration. That is, NASA's cost risk is more limited in a commercial acquisition, but putting together space exploration missions always carries the risk of being able to develop a host of systems, technically, in relevant timeframes, sustainably.

This issue of program risk when integrating commercial elements into a space exploration plan is beyond the scope of this paper and requires extensive attention. A significant consideration that should inform such an assessment includes the well-documented ways in which biases irrationally affect decisions involving some kinds of risks.

Risk aversion biases routinely underweight moderate and high probabilities relative to sure things, reducing the attractiveness of positive gambles.[41] Yet the "sure thing" of a traditional cost-plus contracting approach may as well be surely unaffordable, carrying the risks of low actual yearly funding, meaning stretched timelines, irrelevance, being overcome by events and potential cancelation as high initial cost estimates go even higher.

Zero-risk biases will irrationally choose a complete elimination of a risk even when alternative options produce a greater reduction in overall risk,[42] in the big picture. Stakeholders must agree on the complete picture of risks, their likelihood, and their consequences for the success of a NASA's space exploration planning. Framing a space

exploration plan a certain way can seem to make a risk go away, when actually the risk has merely been assumed away – i.e., assume a high level of funding is eventually approved, then make any discussion about the risk of obtaining initial funding or sustaining funding verboten.

When "risk as feelings"[43] wins over a cognitive assessment, the distinction possible is to approach or avoid, when a cognitive analysis is required that distinguishes true from false.

## III. The Data

Cost analysts live and die by their data, by the facts. Even before analyzing future options, before performing any cost estimate, anyone can just look at historical, real world, raw data, which often speaks for itself. A rigorous review of the costs and value of recent commercial programs concluded - "By isolated measures or by the most holistic measures, the ISS cargo partnerships are a significant advance in affordability and the ISS commercial crew partnerships appear just as promising."[44] Figure 2 and Figure 3 show recent commercial spacecraft acquisition costs (as a service ride, minus launch vehicle) alongside a recent cost-plus program (Orion) and much older cost-plus programs (Apollo). The data shown is in a relatively raw state with–

- A mix of capabilities, low Earth orbit to deep space
- A mix of functionality, capsules / service modules or a lunar lander, cargo or crew
- A mix of contracting approaches, cost-plus or commercial
- A mix of life cycle cost completeness, cost-plus items only through delivery of hardware to NASA, commercial costs with total service costs including launch through mission end

Questions must first be clear to get useful answers – what is the purpose of the cost analysis, what are the limitations of the data? As well, the usefulness of any data is in knowing what to do with it. Any cost analysis considering how raw historical data might apply to new, proposed spacecraft must at least address the matters of capability, function, acquisition / contracting approach and scale, how much smaller or larger than the relevant data points.

Understanding the uncertainty in data is important toward appreciating it's limitations. It's expected that NASA knows exactly what the Apollo Command/Service Module (CSM) and Apollo Lunar Module (LM) cost, but this is not so. Multiple credible data sources lead to different answers,[45,46] especially once the question gets more detailed, like how much these cost to develop versus per unit.

Accounting changes over time add to uncertainty. In 2007, NASA made major accounting changes in it's bookkeeping of project costs. After this date, NASA no longer charged many agency indirect support costs to projects. These indirect costs now had their own budget line. This means that for the raw data in Figure 2 and Figure 3, any non-Apollo data, regardless of being cost-plus like Apollo or commercial, is lower on a comparable basis than using the older Apollo accounting approach (or inversely that the Apollo data would be lower by the latest bookkeeping). Experience also indicates that this may just have been one of numerous smaller bookkeeping changes over time, adding more uncertainty.

Addressing these questions and factors brings us to methodology.

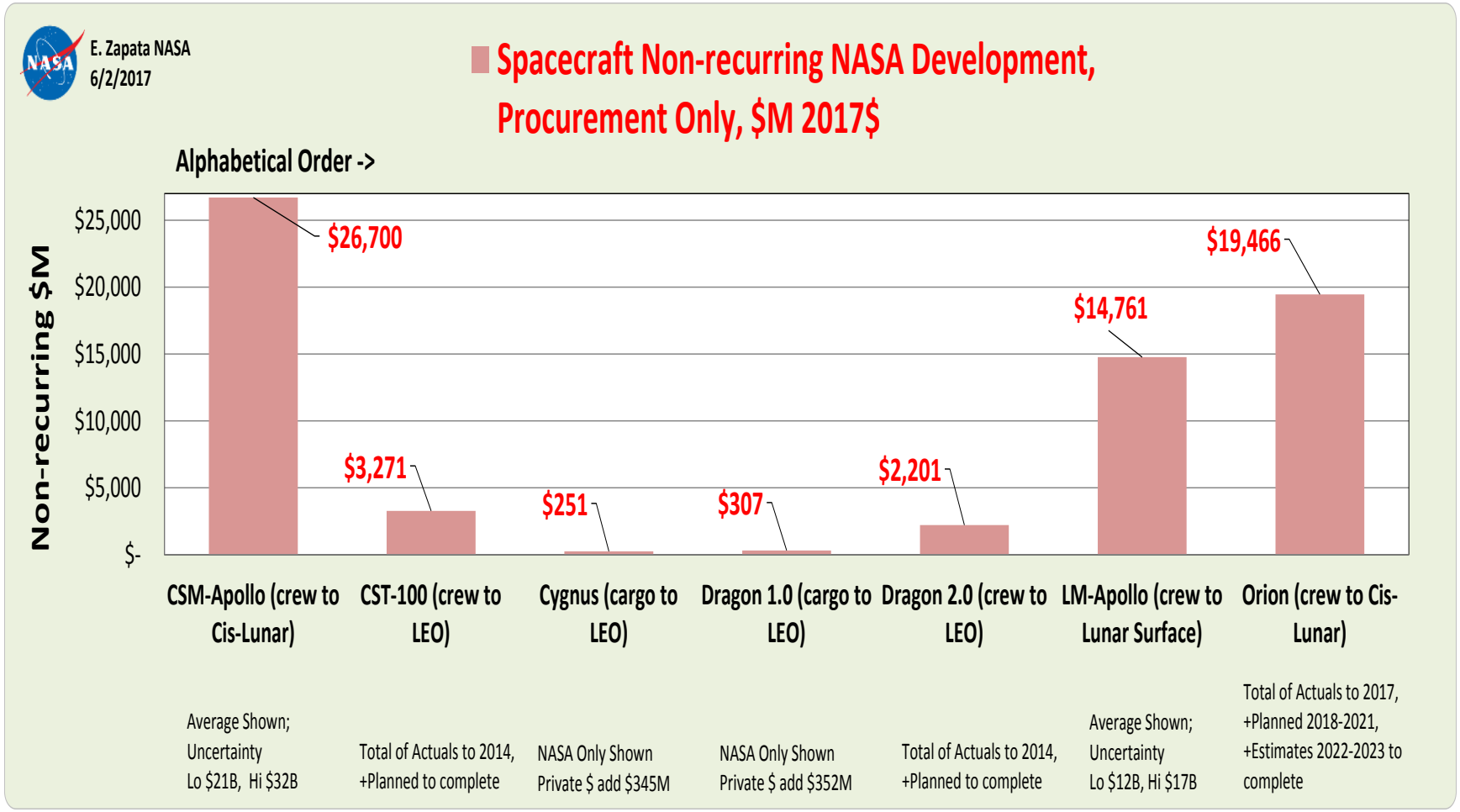


**Figure 2. Up-front spacecraft development costs to NASA.** The Apollo data are averages, with low/high noted, as credible sources differ. Projects in progress, the commercial crew CST-100 and the Dragon spacecraft are actual costs to date and expected costs to completion. Commercial cargo spacecraft costs, Cygnus and Dragon (cargo), are NASA development costs, with private partner contributions noted.

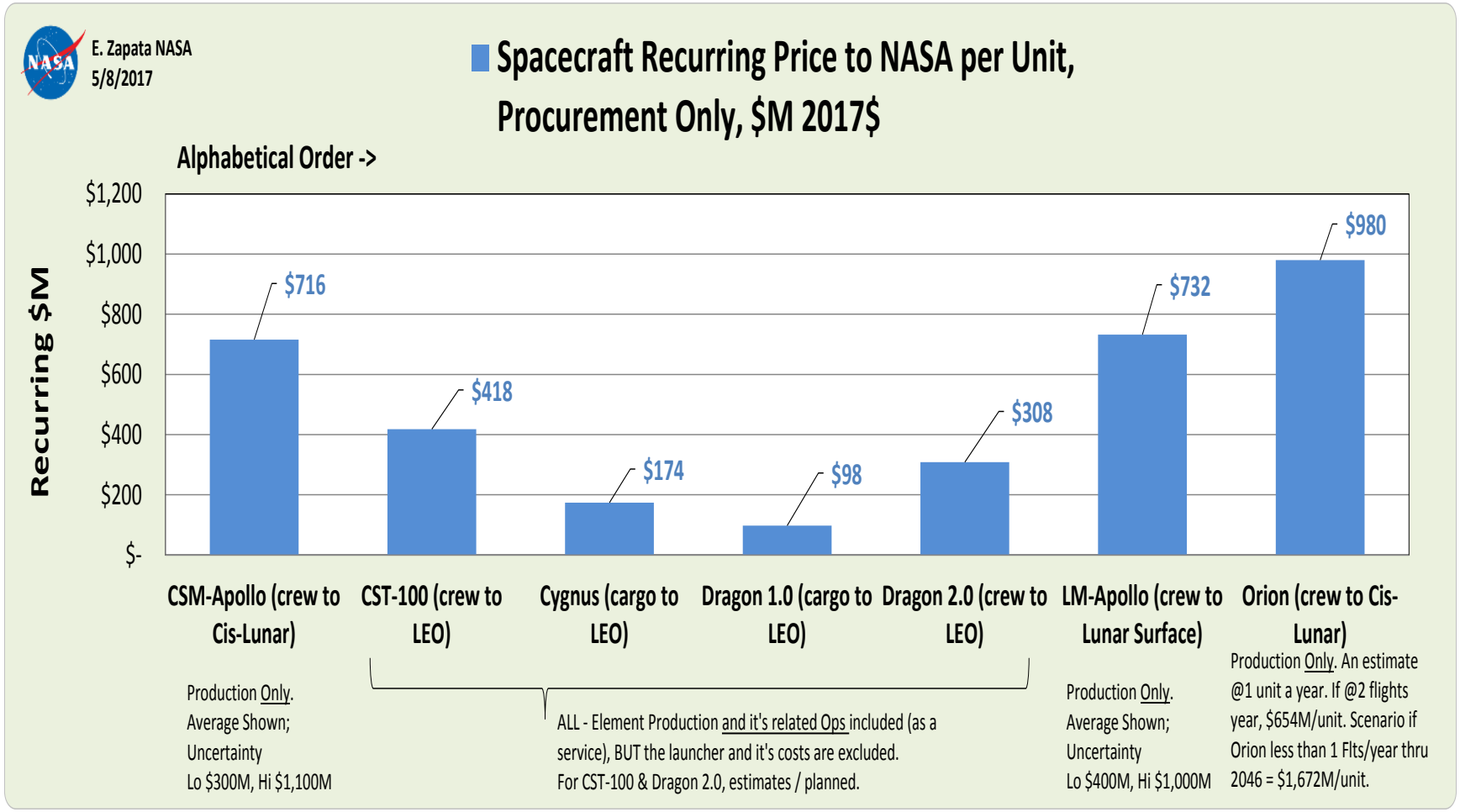


**Figure 3. Per unit spacecraft costs to NASA.** Excludes launchers. The Apollo data are averages, with low/high noted, as credible sources differ. Projects in progress, the commercial crew CST-100 and the Dragon spacecraft are estimates. As cost-plus and commercial items are mixed here, note where the cost per unit is for production only (Apollo, Orion) with the cost-plus item delivered to the government and further costs to integrate and prepare not included, versus the delivery of a service (commercial cargo, commercial crew) where costs are total, through end of mission.

## IV. Methodology

The immediate objective of the cost analysis that follows is to estimate rough-order-of-magnitude (ROM) costs for developing and using an assortment of space exploration capabilities with either cost-plus or commercial contracting. The intent of this analysis is to provide insight, supporting NASA leadership, strategic planning, stakeholders inside and outside NASA, and other non-cost analysts (performance, mass, technology selection, etc.) Strategic planning, developing space exploration options that assemble many space systems, budget planning to see how all these systems might fit within likely budgets, and planning when space exploration milestones are achievable, can use these cost estimates. As important is the difference between estimates, how they differ relative to each other, yet arising from a consistent method. Very early cost analysis based on top-down approaches may have greater consistency (precision) than absolute correctness (accuracy). Nonetheless, decision makers in a budget-constrained environment still benefit assuming they value more affordability over time, and sooner more than later, versus absolutely certain values. Bounding a problem is about intention, intentions about affordability, safety, reliability, and relevance, sooner versus later. These cost analysis are about assisting in bounding a problem, in establishing intentions around space exploration systems costs. Control is not the intention here, an activity that would follow – keeping in mind "no plan survives contact with the enemy."

The overall methodology in extrapolating new space systems from historical data is a mixture of analogy and parametric, appropriate[47] at this level of analysis. Figure 4 notionally summarizes the approach. Other reports cover the gathering of historical data, its review, parsing and organizing in detail.[48] The emphasis of the work here is the challenge of what to do with the data at hand. Developing estimating relationships and extrapolating the cost of new systems from what we have learned and what data we have, are the principal difficulties in developing a methodology.

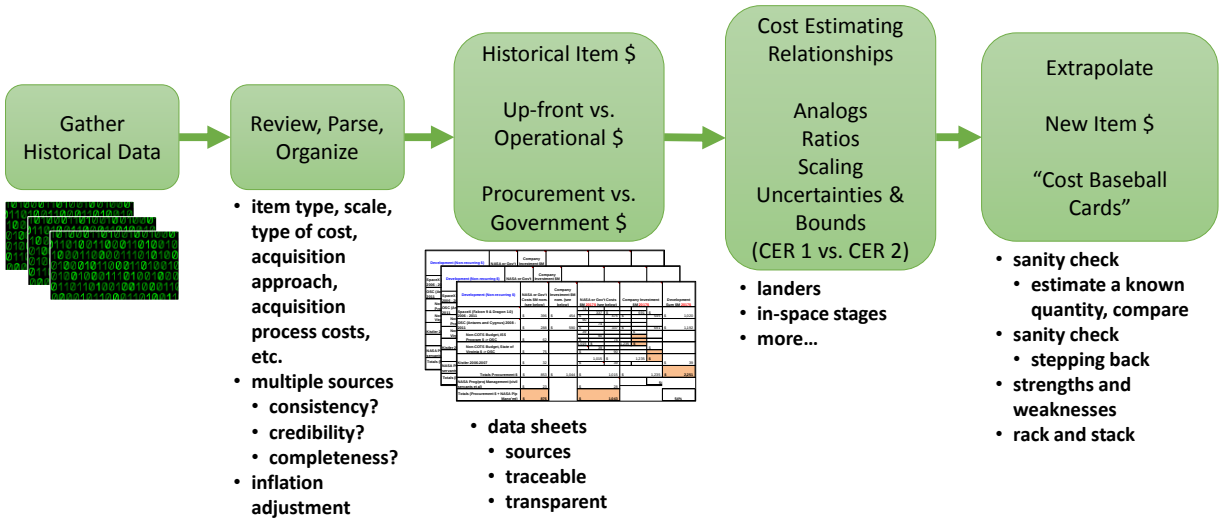


**Figure 4. Methodology for estimating costs for new systems with a public private partnerships / commercial approach or with a traditional / cost-plus approach.**

Reviewing the data guided the development of cost estimating relationships. Beyond costs, analysts will see indications of –

- **Mass and scale**: NASA data in Figure 2 and Figure 3 reveals what complex (cargo) and very complex (crew) systems of (somewhat) known mass cost to develop and per unit, that is the cost per kg of developed hardware and cost per kg of procured units.
- **Complexity**: Experience with deep space elements, the Apollo data points, reveals that a deep space spacecraft costs more to develop than its mission matching lunar lander (Figure 2), but both cost about the same per unit on a recurring basis (Figure 3).
    - This may be a reflection of differences in complexity and/or operating environments (re-entry into the atmosphere vs. not), but we should not discard other factors like unique contractor experience or other practices and efficiencies.
    - We also know that the performance of both elements as a set, especially their delta-v total, a spacecraft and a lander, completes their mission requirement.

- **Uncertainty**: The data points have different kinds of uncertainties.
  - For Apollo items, multiple credible data sources lead to different answers,[49,50] especially once the question gets more detailed, like how much these cost to develop versus per unit.
  - For two spacecraft with practically identical requirements, CST-100 and Dragon (crew), we have different costs.
    - While we know costs to date, their cost to completion and per unit costs have some artifacts in their data that create uncertainty.
    - These are commercial data points from different companies.
  - For two spacecraft that have similar (but not identical) requirements, Apollo CSM and Orion, we have different costs.
    - While we know the costs to date for Orion, the cost to completion and eventual per unit costs are very uncertain.
    - There has been different bookkeeping / accounting for costs over the years.
    - These are cost-plus data points from different companies.

Some of the prior observations on the data are mixed, for example, the CST-100 and Orion have different requirements but they are both developments in an era with the same accounting practices. The Apollo CSM and Orion are both closer functionally and contractually, but their data are from different eras in NASA's accounting practices.

From reviewing the data in the context of its limitations, we developed a methodology focused on locating the *boundaries of the cost challenges*, generating a *range of costs* for new deep space systems judging by the data available. Similar to the solution to NASA's solar flare prediction problem,[51] successfully reimagined as a data challenge, not singularly as a problem predicting flares, the method here stresses the data challenge, not the problem predicting costs. There is data, very old, recent and ongoing, cost-plus and traditional, or from non-traditional partnerships, across companies long established and new, for many different space systems. The problem is figuring out what the jumble means to inform the course forward for NASA and it's deep space exploration elements.

For example - what might be the range of costs of a lander, of certain scales, if done using a cost-plus contracting approach, if done using a public private partnership, if done with less cost efficiency, or more? Generically for other elements –

"*what is the range of costs for assorted new elements, at assorted scales, with assorted acquisition approaches?*"

To resolve this, the methodology –

1) **Focuses on locating cost bounds**: If given two ways of performing a calculation, do both. A range representative of best to worse case is of greater value than any single point cost estimate.
2) **Avoids the matching set / delta-v problem entirely**: Any individual space system, a lander, a stage, etc., is by necessity tightly coupled to other elements in order to fulfill a mission. What performance is lacking in one element (propellant, etc.) is performance the next element must make up. What speed we don't get from element A, we have to get from element B. It is not the purpose of this analysis to connect all these dots, nor is it necessary to bound a range of possible costs.
3) **Prefers ratios**: The use of ratios often cancels out certain estimating issues that otherwise create too many caveats to provide useful results.
4) **Does sanity checks**: Don't let a complex calculation go unchallenged. Step back and check results against other sources, see how the method would calculate a known quantity, and ask what the back-of-the-napkin from a simple perusal of the raw data would have lead to.

The result of these extrapolations are cost ranges where estimates are best used when kept in the context of other estimates in the same *costed* "baseball card". Specific performance considerations, how a spacecraft and a lander, or how these and a propulsive stage, are specified with the performance necessary for a lunar mission will inevitably mean different scale, design and other factors than the items presented here. Assessing the applicability of the methodology and re-running the analysis is required at that time for these variations on a theme. Caveats, especially uncertainties and interpretation, vary from item to item and each baseball card documents these. The costed baseball card that results is similar in format to the traditional element baseball card shown in Figure 5. For contrast, Figure 6 shows an example costed baseball card focused on non-technical information, primarily costs.

The costed baseball card, unlike its doppelganger baseball card focused on mass and performance, is for assorted scale of systems across assorted acquisition approaches. More generally, applying relatively consistent estimating relationships achieves the desired output - as a range of cost from a low to a high. A singular cost estimate for a singular system would weaken the overall value and insights from the card, hiding any context and losing the opportunity to compare and contrast costs left/right (scale) or up/down (acquisition approach).

**Figure 5. An example traditional space system baseball card focused on technical information.**[52] Technical, performance information usually emphasizes mass, plus other characteristics like mission duration or crew capacity. Were this a propulsion stage there would be an emphasis on masses and type of propellant, plus other characteristics like engine thrust or number of engines.

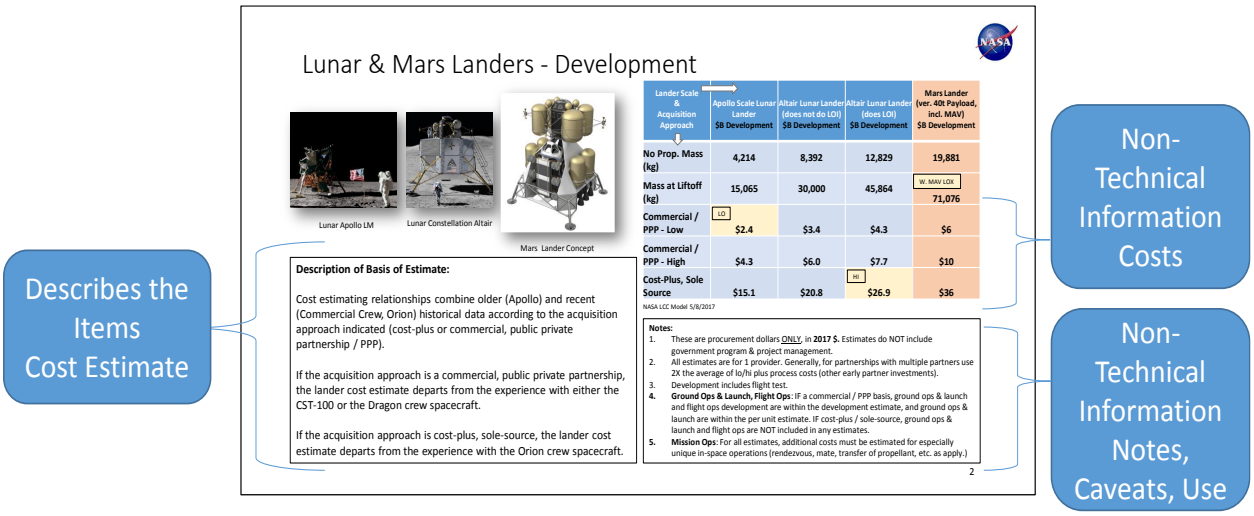


**Figure 6. An example *costed* space system baseball card focused on non-technical information, primarily costs.** Non-technical cost information includes a description of the basis of estimate plus notes and caveats for using the cost estimates.

## V. Landers

The costed baseball cards in Figure 8 and Figure 9 show a range of landers of various sizes with their costs estimated for a range of acquisition possibilities, low and a high estimates with commercial / public private partnerships and an estimate with a cost-plus acquisition approach. In keeping with the methodology valuing sanity checks, a reader or analyst might immediately ask (1) what the Apollo LM cost to develop, versus what the estimating relationships give, and (2) what other studies have estimated for the cost of lunar landers. The Apollo LM historical data is not absolute, with competing but credible sources especially when moving away from top-line budgets into development versus production. The Apollo LM historical cost data indicates a development cost of between $12.5 billion and $17.0 billion in 2017 dollars with an average of $14.8 billion. The cost estimating relationships developed for this analysis yield an answer slightly higher than the average, cost-plus, sole source, Apollo scale lunar lander, at $15.1 billion (overshooting by 2%). This is a trivial check, showing the estimating relationships does not stray far from its primary data.

More useful, an analyst would compare these cost estimates for lunar landers shown in Figure 8 to those in the literature. As this is the first time estimating the cost of these items with this method and in partnership acquisitions, this sanity check is useful only for the cost-plus contracting approaches. Weppler et al[53] placed the cost of an Altair lunar lander at $12 billion in 2009, significantly less than the $20.8 billion here for the "Altair Lunar Lander (does not do LOI[**])". Notably though, other estimates in the same study have been shown with time to cost significantly more, items such as Orion or the canceled Ares I launcher. As of this date, Orion will have a cumulative estimated cost for development (2006-2023) of about $22 billion (in 2017$). Naturally, the Altair lunar lander cost-plus sole source estimate is departing from this recent experience as even though Orion's costs improve over its close cousin Apollo CSM ($26.7B, Figure 2), that improvement does not lead to a cost-plus sole source lunar lander in the $12 billion dollar range. Other Altair lander estimates in the literature at $ 8 billion,[54] estimated using the NASA Air Force Cost Model, would also have similarly sub-estimated the recent reality check and pause given by Orion's cost-plus data.

Put more simply, we know from Apollo that a lunar lander should cost less to develop than its accompanying spacecraft (in an architecture where these are two separate vehicles). However, larger landers like Altair should cost more than the smaller Apollo lander from this rule of thumb. Judging by NASA's most recent cost-plus sole source experience, Orion, facts on the ground vs. a models "should cost" estimate, a cost-plus sole source $21-27 billion dollar Altair passes it's sanity check.

Commercial crew spacecraft are the other bookends here. Using the same Apollo ratios (spacecraft/landers) and scaling factors as with cost-plus, but with commercial cost data, different costs naturally result - from $2.4 billion to $7.7 billion across a scale from the smaller Apollo LM to the largest Altair (does LOI). A few important caveats give pause. The bargain basement lunar lander for $2.4 billion, a commercial acquisition of a design of the same scale and function as the Apollo LM, may only be possible by funding multiple early competitors, then having two partners in development, and two providers for production units. This is an arrangement seen in the COTS partnerships.[55] This would bring the programs costs for the smallest Apollo LM-like lander up to over twice the average of the lowest cost ($2.4 billion) and the next lowest cost ($4.3 billion), or a total of at least $6.7 billion before other acquisition process costs. Examining the requirement for two providers as part of public private partnerships would be valuable forward work before a lunar lander acquisition, but is beyond the scope of the analysis here.

A similar large range of results is shown in Figure 9 with lunar lander unit manufacturing, from $600M a unit (commercial) to over $2 billion a unit (cost-plus), with a new wrinkle. The data for the commercial points of departure, complex spacecraft like the CST-100 Starliner, is for a turnkey service, including integration, mission operations and the associated ground operations along the way. We removed launcher costs from the program data (recalling that these commercial programs acquire whole end-to-end services, not individual items like launchers or spacecraft per se). The manufacturing data for Apollo or estimated for Orion does not include any of these integration, mission operations or ground operations along the way. The nature of a cost-plus contract has the item delivered to the launch site. Once at Kennedy Space Center (KSC) the item changes hands in a process that transfers ownership of the item from the contractor to NASA and the US Government. This handover does not occur in public private partnerships where the analogy is more to a rental car or lease, not a purchase with ownership (or some might go as far as saying the commercial analogy is to a chauffeur service, with self-driving features engaged).

As with development, it may be best to view the bargain basement lunar lander at $600M a unit as part of a matched set. A second provider could be involved in the program at the higher commercial prices for the sake of redundancy, or especially for a proper alignment of incentives, making these lower prices (especially up-front) possible.

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[**] LOI = Lunar Orbit Insertion, referring to how much of the trip's propellant burden is picked up by the lander versus other parts of the system that leave Earth orbit, like the departure stage or crew spacecraft.

In keeping with sanity checking results, a first test would note that the Apollo spacecraft and landers had similar per unit costs. For the commercial case, we would expect landers to cost at least as much as the CST-100 or the Dragon/crew the calculations depart from. The lander values though are higher at the best case and significantly higher in the worst case. This is odd only until considering and adjusting for scale. Scale has to take into account that the commercial spacecraft data points are for low Earth orbit spacecraft, not deep space spacecraft, which would scale up for additional mission requirements. The landers at the worst case are also up to 3X times as large as the Apollo LM, with the "Altair Lunar Lander (does LOI)" coming in at over 45 tons compared to the 15 ton Apollo LM. With this in mind, the results are sane, albeit scaling factors are an area ripe for forward work and refinements. In the spirit of a devil's advocate, the analysis looked at the results from the cost estimating relationships against even simpler sanity checks as shown in Figure 7.

For all cases, the landers in Figure 8 and Figure 9 are expendable landers. Forward work could improve the relatively simple estimating from either cost-plus or commercial experience for reusability as well. Related and stepping back even more, the traditional crew spacecraft/lunar lander attached and on their way to the Moon where the lander separates is just one possible technical approach. While the redundancy in having two spacecraft along for the trip may allow for certain Apollo 13 style recoveries from near catastrophe this is in no way a requirement. Reliability growth and other redundancies could open the door to single-stage landers, complete with all propulsive capability, departing from Earth orbit. The lander baseball cards bound this problem in concert with the costed baseball cards for stages covered ahead.

Similarly, we have extrapolated Mars landers in the last column of Figure 8 and Figure 9. Although stretching the basic cost estimating relationships, analogs and ratios, a preliminary range of costs for Mars landers consistent with the data at hand shows how promising partnerships might be versus a cost-plus alternative. By way of sanity check on the estimating relationships using the cost-plus case, a 2015 Jet Propulsion Lab cost estimate for a same scale and type of Mars lander was $44B (through a first Mars long-stay mission).[56] This is close to the cost-plus estimate here for only the Mars lander development, ~ $36B arrived at by different, independent estimating relationships. This supports the credibility of the estimates here at a gross level.

Lastly, before using any of these results it's important to contact the analyst to assure the numbers are used properly. The low/high estimates for the commercial approaches capture more uncertainty, from data that was in one phase or another part of firm fixed price contracts. There is no reflection of uncertainty, like with low/high or three-point estimates, for the cost-plus extrapolations, even though by definition these contracts often have an uncanny ability to rise over time.

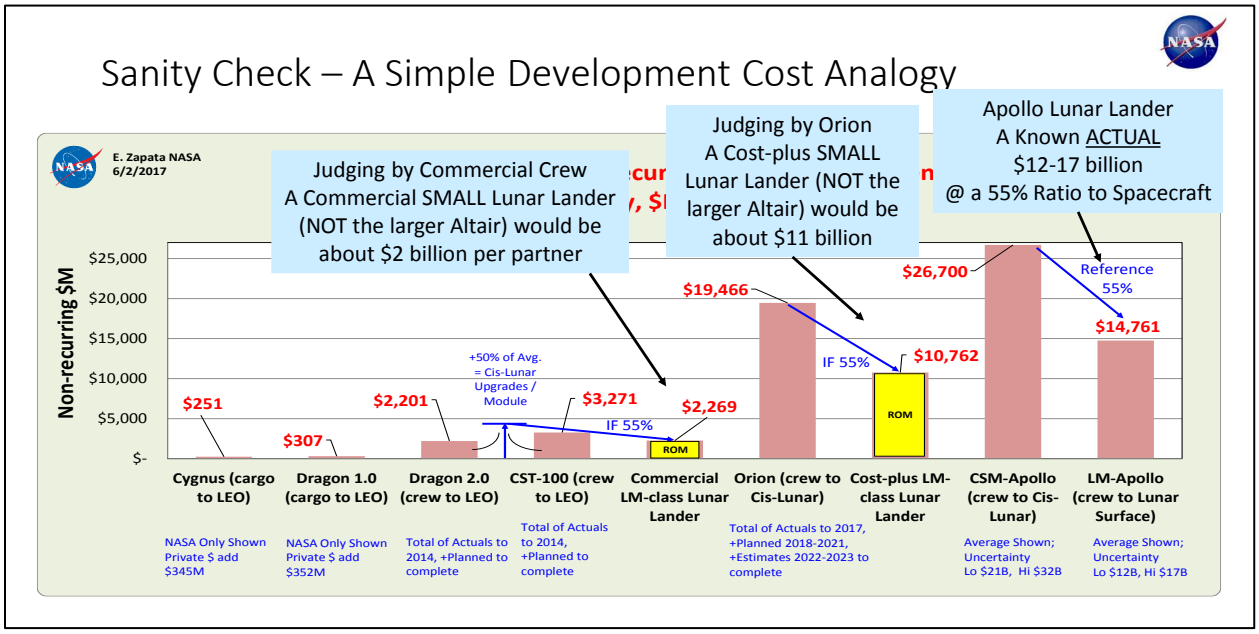
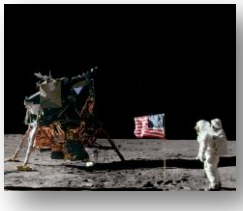
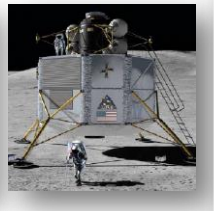



**Figure 7. A simple example sanity check of results.** Stepping back to look at the range of costs for a small lunar lander based simply on ratios give's answers somewhat less than the answers calculated with more rigorous cost analysis that considers scale and complexity. However, this provides a useful sanity check. This is at least the cost for any estimates consistent with the Apollo spacecraft/lander cost ratio before addressing other factors and adjustments.

# Lunar & Mars Landers - Development



Lunar Apollo LM



Lunar Constellation Altair

Mars Lander Concept

**Description of Basis of Estimate:**

Cost estimating relationships combine older (Apollo) and recent (Commercial Crew, Orion) historical data according to the acquisition approach indicated (cost-plus or commercial, public private partnership / PPP).

If the acquisition approach is a commercial, public private partnership, the lander cost estimate departs from the experience with either the CST-100 or the Dragon crew spacecraft.

If the acquisition approach is cost-plus, sole-source, the lander cost estimate departs from the experience with the Orion crew spacecraft.

| Lander Scale & Acquisition Approach | Apollo Scale Lunar Lander $B Development | Altair Lunar Lander (does not do LOI) $B Development | Altair Lunar Lander (does LOI) $B Development | Mars Lander (ver. 40t Payload, incl. MAV) $B Development |
|---|---|---|---|---|
| No Prop. Mass (kg) | 4,214 | 8,392 | 12,829 | 19,881 |
| Mass at Liftoff (kg) | 15,065 | 30,000 | 45,864 | W. MAV LOX 71,076 |
| Commercial / PPP - Low | LO $2.4 | $3.4 | $4.3 | $6 |
| Commercial / PPP - High | $4.3 | $6.0 | $7.7 | $10 |
| Cost-Plus, Sole Source | $15.1 | $20.8 | HI $26.9 | $36 |

NASA LCC Model 5/8/2017

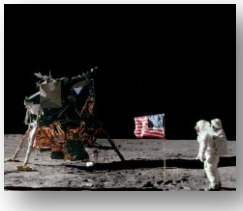
**Notes:**

1. These are procurement dollars ONLY, in **2017 $.** Estimates do NOT include government program & project management.
2. All estimates are for 1 provider. Generally, for partnerships with multiple partners use 2X the average of lo/hi plus process costs (other early partner investments).
3. Development includes flight test.
4. **Ground Ops & Launch, Flight Ops**: IF a commercial / PPP basis, ground ops & launch and flight ops development are within the development estimate, and ground ops & launch are within the per unit estimate. IF cost-plus / sole-source, ground ops & launch and flight ops are NOT included in any estimates.
5. **Mission Ops**: For all estimates, additional costs must be estimated for especially unique in-space operations (rendezvous, mate, transfer of propellant, etc. as apply.)

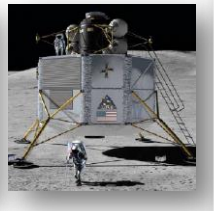
2

**Figure 8. Lunar and Mars Landers costed baseball card for up-front non-recurring development costs.** Included are a range of variations in scale and functionality, cost-plus vs. partnerships, and some low vs. high estimates.

# Lunar & Mars Landers - Manufacture



Lunar Apollo LM



Lunar Constellation Altair

Mars Lander Concept

| Lander Scale & Acquisition Approach | Apollo Scale Lunar Lander $B per Unit | Altair Lunar Lander (does not do LOI) $B Per Unit | Altair Lunar Lander (does LOI) $B Per Unit | Mars Lander (ver. 40t Payload, incl. MAV) $ B per Unit |
|---|---|---|---|---|
| No Prop. Mass (kg) | 4,214 | 8,392 | 12,829 | 19,881 |
| Mass at Liftoff (kg) | 15,065 | 30,000 | 45,864 | W. MAV LOX 71,076 |
| Commercial / PPP - Low | LO $0.6 | $0.8 | $1.0 | $1.4 |
| Commercial / PPP - High | $0.9 | $1.3 | $1.7 | $2.3 |
| Cost-Plus, Sole Source | $1.3 | $1.8 | HI $2.3 | $3.1 |

NASA LCC Model 5/8/2017

**Description of Basis of Estimate:**

Cost estimating relationships combine older (Apollo) and recent (Commercial Crew, Orion) historical data according to the acquisition approach indicated (cost-plus or commercial, public private partnership / PPP).

If the acquisition approach is a commercial, public private partnership, the lander cost estimate departs from the experience with either the CST-100 or the Dragon crew spacecraft.

If the acquisition approach is cost-plus, sole-source, the lander cost estimate departs from the experience with the Orion crew spacecraft.

**Notes:**

1. These are procurement dollars ONLY, in **2017 $.** Estimates do NOT include government program & project management.
2. All estimates are for 1 provider. Generally, for partnerships with multiple partners use 2X the average of lo/hi plus process costs (other early partner investments).
3. Development includes flight test.
4. **Ground Ops & Launch, Flight Ops**: IF a commercial / PPP basis, ground ops & launch and flight ops development are within the development estimate, and ground ops & launch are within the per unit estimate. IF cost-plus / sole-source, ground ops & launch and flight ops are NOT included in any estimates.
5. **Mission Ops**: For all estimates, additional costs must be estimated for especially unique in-space operations (rendezvous, mate, transfer of propellant, etc. as apply.)

3

**Figure 9. Lunar and Mars landers costed baseball card for recurring manufacturing and operations costs.** Included are a range of variations in scale and functionality, cost-plus vs. partnerships, and some low vs. high estimates.

## VI. Stages

Figure 10 shows a range of in-space propulsive stages of various sizes with their costs estimated for a range of acquisition possibilities. As with landers, a costed baseball card, unlike its doppelganger baseball card focused on mass and performance, is for assorted scale of systems across assorted acquisition approaches. The commercial experience with the Falcon 9 in the COTS program, in the Evolved Expendable Launch Vehicle (EELV) program with the Delta IV, and the cost-plus experience on going in the Space Launch System (SLS) program primarily drive the results. A new wrinkle in these estimates is adjusting for complexity when (1) moving away from a purely propulsive in-space function to in-space stages that also perform a refueling/tanker function, (2) moving away from Rocket Propellant (RP) fuel to cryogenic propellants (Liquid Hydrogen/LH), and (3) moving beyond a single use refueling stage/tanker to long duration propellant depots. The complexity factors require expert judgement, values from 1.0 when not deviating from source data to multiples for depots significantly beyond the functionality of just a one-use in-space stage. Stages are place ordered by scale, not function. So for example, a small depot is alongside small stages and a large depot is with larger stages.

Only one cost-plus point was tackled in this analysis of potential in-space propulsive stages - the SLS's Exploration Upper Stage (EUS). As with the landers analysis, heavily dependent on the most recent cost-plus crewed spacecraft Orion, the EUS cost-plus / sole source estimate is heavily dependent on the most recent and related cost-plus / sole source launch system, the SLS. The SLS historical data (budgets 2011-2016) and budget planning through completion of development will total $18.5 billion (in 2017$). As with all data in this analysis, these are procurement (contractor) dollars exclusive of NASA management (personnel/civil servants) and other NASA related execution costs. While it may strain credibility to have an estimate for the development of a stage of this size in the few billion dollars range, this independent estimate here is consistent with other estimates for a similar cost-plus system.[57] To date the NASA EUS budget was $85M[58] for 2016 and $300M[59] for 2017. Data for 2018 forward will inform the cost estimate here for further development to completion in the early 2020's (knowing final total budgets/costs will have been for both SLS and its EUS and some of these may be fungible across elements).

The other cost estimates are for items procured using commercial / public private partnerships (PPP). Most of the caveats about lander cost estimates also apply here. Partnerships have process costs, partners funded early on but not further. Partnerships may have two developments and then two providers. Biases in some of these numbers arise from the departure point, the Falcon 9 experience, documented as a significant detour from the costs usually expected for such systems.[60] A second provider might have costs higher than the lowest values in the in-space stages costed baseball card, but not as high as a cost-plus scenario.

Some curious effects occur as scale and complexity both influence cost estimates. Note that by this analysis a small propellant depot costs more than a much larger stage with the same commodities. Uncertainty in a propellant depot, from propellant management to propellant transfer operations, justifies a conservative (high) complexity factor. This is consistent with locating the bounds of the different costs of stages, projects that may do worse than the COTS Falcon 9 experience or better than the conservative assumptions on the propellant tankers and propellant depot technology.

The results open up important questions. For example, a cost-plus arrangement delivers hardware manufactured by a contractor elsewhere to NASA at KSC. The hardware switches hands at a certain milestone in the contract and becomes US government property. While other contractors in ground operations perform processes to get the hardware ready for launch, the element remains government property. A Shuttle stack involved Solid Rocket Motors from one contractor, an External Tank from another, Orbiter's from a company that eventually ceased to exist, absorbed into another, and engines from Rocketdyne that at one point had turbo-pumps from its competitor Pratt & Whitney. This begs the question of a commercial option for the SLS EUS. The notion the upper stage and core stage are too tightly integrated, justifying a cost-plus/sole source contract, is questionable by history. As with the Shuttle's multiple companies manufacturing major elements, three different contractors (Boeing, North American and Douglas) built the Saturn V's three stages – also a tightly integrated system. A revised acquisition approach for the EUS is a topic worthy of discussion, potentially bringing the EUS into the realm of the cost estimates using public private partnerships. Inevitably, this question would have to explore a business case beyond just NASA and the SLS, noting that the current scale of the EUS could also function as a derivative tanker in a propellant depot infrastructure. It's for this reason that assorted scales were analyzed as shown in Figure 10.

Other important questions include questioning the scale of an in-space stage that might have the largest customer base. NASA's direction, lunar or Mars, with or without refueling, and with or without a depot accumulating propellant (refueling a stage direct from a tanker or another stage) can affect right sizing an SLS upper stage. That stage or its close derivatives may have more than just NASA as a customer. Again, we see refilling of stages in a recent concept, SpaceX's idea for an Interplanetary Transport System.[61] NASA explored this refueling concept in numerous NASA

studies, in 2010 with an emphasis on the departure staging,[62] and in 2011 as an option to fit an entire Mars exploration architecture into constrained NASA human spaceflight budgets.[63]

By extension, as all the stages and tankers analyzed are expendable, but depots are reusable across multiple missions, forward work would address design life factors. Reusable in-space stages are not beyond the realm of what's possible, and sooner than what might have been considered achievable years ago.[64] A greater degree of reusability may enable Ultra-Low Cost Access to Space (ULCATS)[65], moving beyond the experience of reusing an orbital spacecraft (like the Shuttle orbiter) or a booster stage (like the Falcon 9).

In general, as the estimates in the costed baseball card for stages continue to evolve:

- **Relative Cost Estimates**: It's best to consider these propulsive element cost estimates relative to each other, much more so than using individual element cost estimates without this context.
- **Production Volume**: Volume of production is a variable that can significantly affect these cost estimates; future work could refine this aspect.
- **Commonality**: Commonality across these elements, manufacture by the same company, and how the business case for some low production rate elements might depend on higher production rate elements, also requires further consideration.

# In-space Stages

Delta IV 5m Upper Stage

Falcon 9 Upper Stage

SLS Upper Stage
(planned, the "EUS")

**Description of Basis of Estimate:**
Cost estimating relationships use recent historical data according to the acquisition approach indicated (cost-plus, sole-source or commercial, public private partnership / PPP).

**Notes:**

1. These are procurement dollars ONLY, in **2017 $**. Estimates do NOT include government program & project management.
2. All estimates are for 1 provider. Generally, for partnerships with multiple partners use 2X the average of lo/hi plus process costs (other early partner investments).
3. Development includes flight test.
4. **Ground Ops & Launch, Flight Ops**: IF a commercial / PPP basis, ground ops & launch and flight ops development are within the development estimate, and ground ops & launch are within the per unit estimate. *IF cost-plus / sole-source, ground ops & launch and flight ops are NOT included in any estimates.
5. **Mission Ops**: For all estimates, additional costs must be estimated for especially unique in-space operations (rendezvous, mate, transfer of propellant, etc. as apply.)

| Element | Dry Mass, kg | NASA Acquisition Approach | Development $M 2017 $ | Per Unit Including Launch $M 2017 $ | Prop, kg |
|---|---|---|---|---|---|
| **Tanker LO/LH** for Falcon Heavy, as 3rd stage, as payload | 7,613 | PPP / Commercial | $250 | $67 | 56,187 |
| **Tanker LO/LH** for Falcon Heavy, replacing 2nd stage + payload | 19,136 | PPP / Commercial | $466 | $125 | 141,234 |
| **Tanker LO/LH** for Delta IV Heavy, as 3rd stage, as payload | 3,435 | PPP / Commercial | $622 | $167 | 25,355 |
| **Tanker LO/LH** for Delta IV Heavy, replacing 2nd stage + payload | 7,100 | PPP / Commercial | $890 | $238 | 52,400 |
| **Stage LO/LH,** Smaller | 11,002 | PPP / Commercial | $235 | $63 | 100,000 |
| **Stage LO/LH,** Smaller | 11,002 | PPP / Commercial | $358 | $51 | 100,000 |
| **Depot LO/LH**, Smaller | 11,002 | PPP / Commercial | $1,253 | $336 | 100,000 |
| EUS for SLS, **LO/LH** | 11,854 | Cost-plus / sole source | $3,684 | $263 | 107,328 |
| **Stage LO/LH,** Larger | 18,252 | PPP / Commercial | $337 | $90 | 225,000 |
| **Stage LO/LH,** Larger | 18,252 | PPP / Commercial | $449 | $64 | 225,000 |
| **Depot LO/LH**, Larger | 18,252 | PPP / Commercial | $1,797 | $482 | 225,000 |

Use as a set LO/HI

*See Notes

NASA LCC Model 5/11/2017

3

**Figure 10. Assorted in-space stages costed baseball card for up-front non-recurring development costs and recurring manufacturing and operations costs.** Included are a range of variations in scale and functionality for mostly partnership approaches, except for one cost-plus, sole-source item.

## VII. Pros, Cons & Uncertainty

Cost estimates have leanings; factors analysts know tend to make the numbers higher or lower than they may prove in practice. For estimates that are already attractive, affordable propositions a "pro" would mean the leaning due to data or methodology makes the number even less, that the number is conservative, making it less likely real bids might cause surprise. Alternately, a "con" makes a number climb well beyond initial expectations. Uncertainties are those factors that are less well understood, able to cause an initial cost estimate to go higher or lower, the wild cards. Some major pros, cons and uncertainties for the cost estimates here include:

1) Private capital in public private partnerships (for up-front development):
   - For the lander estimates, private capital *IS NOT* in the point of departure data (items like the CST-100, etc.) Yet we know that these programs are employing private capital of an unknown (proprietary) amount. This means the total effort or capital required for the landers is that amount estimated in the costed baseball cards plus some other unknown amount of private partner contribution – i.e., the costs as estimated are the NASA portion of costs, the total effort likely required being *higher*.
   - For the in-space stages estimates, private capital *IS* in the point of departure data (items like Falcon 9, etc.) This means the amounts estimated lean much higher than what would be the NASA portion of costs, assuming similar partner contribution and "skin in the game" – i.e., NASA costs could be *much lower* than these estimates.

2) Complexity:
   - In all cases, uncertainty occurs in the leap from what we know to new systems. The temptation is always there to say "this time will be different" in estimating the costs for system X. This may be a phenomenon seen more when estimating an item for a cost-plus contract approach, a desire to peel away from a poor experience. In 1999 NASA was upgrading the Checkout and Launch Control System (CLCS) at KSC working to a cost projecting programmers could do 300 lines of code per month. This even though the historical average was 85.[66] Due to cost overruns, NASA eventually canceled this project. Here, the analysis keeps both cost-plus and commercial cost estimates close to their historical data. Where uncertainty is likely highest is in judging the complexity difference between a historical system and the new item, a traditional challenge in cost analysis and an area for future work.

Independent assessment of the Commercial Crew Program by Booz-Allen Hamilton observed - "Estimating "new ways of doing business" encouraged by CCP's alternative acquisition strategy has very limited historical precedence within NASA." Besides costs in a basis of estimate matching cited actuals from a historical program, an estimate must quantify and justify factors applied to historical costs.[67] Consistent with this, the work presented here avoids magic, saying there will be 300 lines of code a month with little or no justification other than optimism and "unobtainium". Transparency improves and strengthens stakeholder understanding of the situation and a cost estimate. A transparent cost estimate is one an outsider can look at and reproduce without getting lost along the way. In the author's experience, outside review helps improve cost estimates. Excel sheets (created by the author) extensively document raw historical data and estimates for new systems derived from that data like the example in Figure 11. Cited sources and checks against other analysis and assessments inform this work and will continue to strengthen future analysis.

*Consistent with this, raw data and derived analysis are available upon request.*

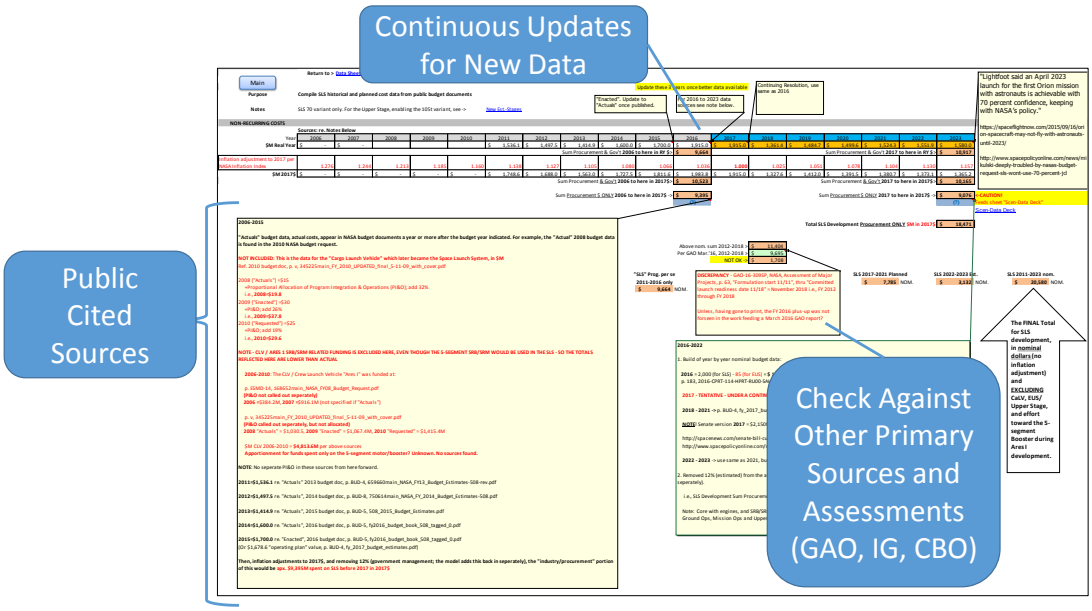



**Figure 11. An example data sheet (SLS).** Data sheets are available upon request. Data for historical systems and derived analysis for new systems document sources and justify factors or adjustments as required.

## VIII. Forward Work: Other Elements & Assessing Appropriate Acquisition Processes

There are many more space systems left to consider for public private partnerships. (According to some think tanks, NASA should "Abandon the use of cost-plus contracts."[68]) Very likely, an objective maturity assessment of industry capabilities combined with an increased acceptance that some partners may fail to deliver and NASA has to switch riders[69] should inform future space systems acquisition planning. The data and method used here to estimate ranges of costs can apply to these other systems and work will continue in this regard.

Besides landers and stages like those covered previously, another major exploration space system is in-space habitation for crew. Crewed habitation systems for deep space share a lot in common with the LEO crewed spacecraft NASA is already funding using partnerships, Dragon, Starliner and possibly Dream Chaser. Adjustments for scale and for the requirements of deep space, including Earth entry, descent and landing, are within the bounds of the data and methodology explored here. Similarly, Orion and the International Space Station provide starting points for estimating the development and manufacturing costs of a habitation system in a cost-plus acquisition paradigm.

Most importantly, the possibility of exploration habitation systems as public private partnerships lies at a critical intersection of opportunities with the ISS. It would be a significant failing if the ISS ended and others did not apply the knowledge gained outside of NASA's needs. There are two significant questions about the intersection of opportunities between the private sector and NASA requirements for deep space habitation.

First, a public private partnership usually includes a policy (if not contractual) commitment by NASA to buy future services. In the case of habitation, this commitment may be direct, acquiring habitation systems on an ongoing basis, but also indirect, acquiring time and space on private sector space stations of similar design. Partnerships to date have seen business cases where the same hardware is shared between NASA and the private sector (SpaceHab in the Shuttle era), where the same system is sold to NASA and the private sector (Falcon 9), and where the systems market beyond NASA has yet to be established (Antares, Cygnus, Dragon cargo & crew, CST-100 crew, and Dream Chaser). Unlike launch (and Falcon 9), habitation would have to lead the creation of a new market rather than capturing sales within an existing market, a more challenging proposition.

A habitation business case for a company, or preferably multiple providers, around a NASA commitment to buy time or space aboard a separate similar facility (in LEO or elsewhere in cis-lunar space) could fall under a NASA anchor tenant paradigm. It would also be consistent with a desire on NASA's part not to abandon LEO space research after the end of ISS. Other customers would also use these facilities. If there is private sector business for these in-space facilities, the companies could offer similar habitation units to NASA at a significant cost savings. That is relative to systems built by only one provider to be owned and used only by NASA, with no opportunity to introduce commercial incentives or to amortize costs over non-government users.

Taking this farther out, the private sector could conceivably build a business case for habitation systems around mature, profit making manufacturing operations. NASA could collaborate with multiple companies for its habitation requirements on the premise that the private sector would use similar design and shared manufacturing lines to make their habitation/modules for in-space manufacturing. This potential private sector business case would encourage the partner to invest private capital in the development of their system, alongside NASA funding, as occurred with commercial cargo and crew, lowering the costs to NASA. There is opportunity to payback private investment assuming a future win providing NASA services, but there is enormous potential to payback private investment if the customer base is practically unlimited.

In-space manufacturing possibilities cross many fields. Medical applications include 3D printing of organs, where the zero gravity environment eliminates the need for a scaffold. Scientists have yet to devise a scaffold supporting the printed organ that can be removed later without damage. Materials applications include especially valuable materials justifying an in-space facility such as exotic fiber optic cable. ZBLAN fiber optic cable, an especially pure form of fiber optic cable, can sell for upwards of a few million dollars per kg.[70]

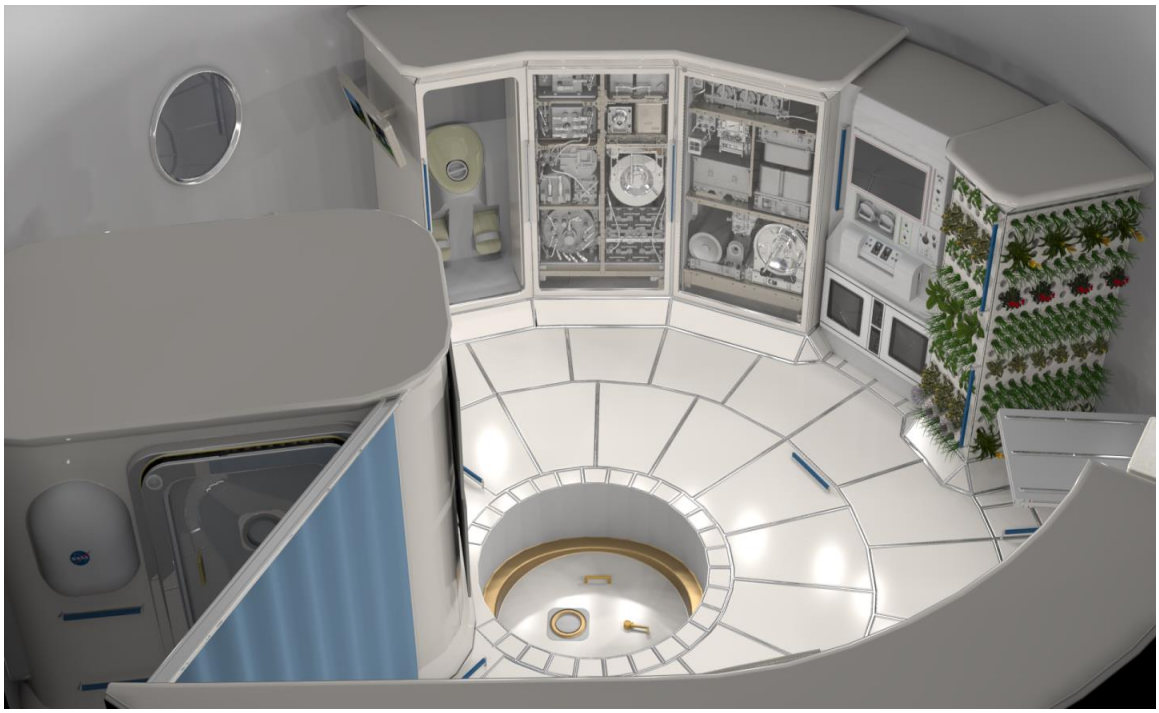


**Figure 12. Visualization of the interior of a Deep Space Habitat.** Image NASA.

NASA has not yet defined a long-term acquisition strategy for an eventual in-space habitat/transit ship, but it is already funding multiple companies developing habitation concepts. These companies are Bigelow Aerospace, Boeing, Lockheed Martin, Orbital ATK, Sierra Nevada and NanoRacks.

Avoiding artificial constraints, the eventual costed baseball card for NASA's in-space habitation (a transit ship, gateway[71], as the naming may be) should run across scales and acquisition approach as already shown in the prior cases. As well, the costed baseball card should also span concepts, from more to less modular, and from more to less integral with other system elements like spacecraft or landers.

Besides other elements of forward work, estimating other system costs using public private partnerships (exploratory probes, habitation for crew on a planetary surface, power and capabilities for processing native resources, etc.), there remains a broader issue.

NASA must develop a formal assessment process to establish how to go about an acquisition in the first place, at the birth of a need. Will the acquisition be traditional, a series of requests for information and bidder conferences with a request for proposals followed by an award of a cost-plus contract, or will it be less traditional, using some other transaction authority, expecting private capital and skin in the game? Will the acquisition be an investment, for a product, for a service? How can NASA assess the appropriateness of an acquisition approach for any outcome, objectively, measurably? What are the appropriate measures, maturity assessment factors and best practices that keep all options on the table when a need is first identified, avoiding a premature decision on acquisition approach?

Current acquisition practice shows a leaning toward traditional approaches even before NASA formally decides on an approach, when the best practice may be to place all options on the table at the start, avoiding a premature decision when information is still lacking. The NASA acquisition tenet "During the development phase of a project, NASA should take on the cost risk because of the difficulty of developing firm estimates for the cost of the work to be performed"[72] shows such a bias toward traditional practice. Likewise, there is a lack of rigor on the applicability and shape of Other Transaction Authority (OTA) in contracting,[73] the kind of approach used in early investments leading to commercial cargo capabilities. Clearly, NASA acquisition processes and estimating life cycle costs using new ways of doing business are topics that must eventually go forward hand in hand.

## IX. Conclusions

Significant cost reductions from the norm of cost-plus contracting are possible for new space system elements in NASA's exploration scenarios. We analyzed landers and stages across scales and types for life cycle costs, development, and manufacturing (some with operations), if these were acquired using commercial / public private partnerships. There is no basis to conclude that public private partnerships end at low Earth orbit, prohibited or incapable of going beyond that point to deep space, the moon or Mars.

Data sheets and cost estimation sheets are available upon request to assure the broadest dissemination of knowledge, further peer review, and continuous improvement of these life cycle cost estimates to date.

Including these commercial options in NASA space exploration architectures, that assembly of many space systems for specific missions, could significantly improve two factors where NASA exploration programs face difficulties. Deep space systems as public private partnerships could significantly reduce the cumulative cost of deep space exploration elements while addressing the risk of irrelevance, as reduced costs equal outcomes that are sooner rather than forever a matter for another generation.

Lastly, it's recommended that NASA acquisition processes avoid prematurely favoring one contracting approach over another, avoiding the preconception very advanced systems must fall under traditional cost-plus like contracting. Partnerships are investments before they might ever be acquisitions. Investment & Acquisition processes should formally place all options on the table and assess NASA needs vs. industry capabilities in a traceable process that creates successful outcomes for NASA while growing the space sector.

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