Breaking the cost curve: applying lessons learned from the James Webb Space telescope development to build more cost-effective large space telescopes in the future

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ABSTRACT

This paper looks at the key programmatic and technical drivers of the James Webb Space Telescope and assesses ways to building more cost-effective telescopes in the future. The paper evaluates the top level programmatics for JWST along with the key technical drivers from design through integration and testing. Actual data and metrics from JWST are studied to identify what ultimately drove cost on JWST. Finally, the paper assesses areas where applying lessons learned can reduce costs on future observatories and will provide better insights into critical areas to optimize for cost.

Keywords: ATLAST, LUVOIR, Exoplanet, HDST, Space Telescope

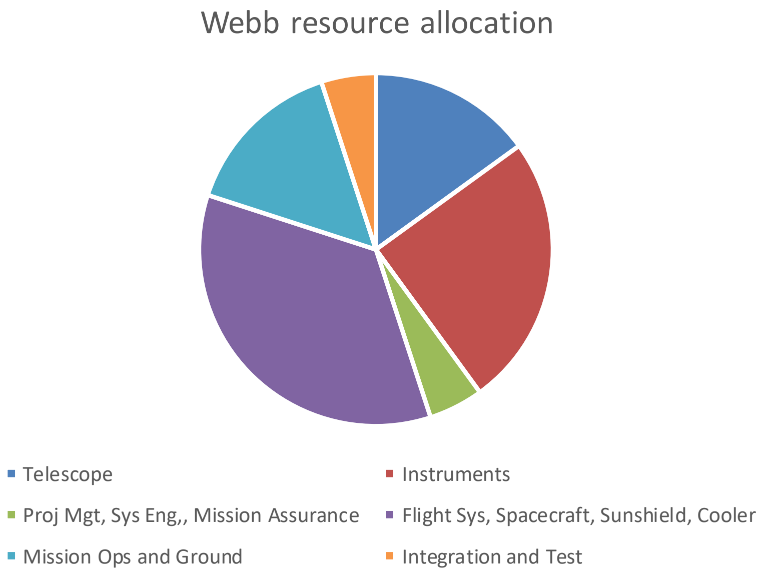
1. INTRODUCTION

As NASA prepares for the next decadal survey, it is worth considering how lessons learned from the James Webb Space telescope (JWST) development efforts can be factored into the architecture and cost assessments for next generation large space telescopes. In the past, cost metrics from smaller, earlier telescopes[i], [ii] have been used to extrapolate costs for larger telescopes. These cost models predict cost largely based on a correlation with the diameter of the telescope and to a lesser extent key metrics like temperature and wavelength. These cost models also are telescope-centric and require additional heritage and mass based cost modeling to assess the cost of the full observatory. However, the parametric cost modeling and heritage based models do not adequately consider many of the actual cost drivers from Webb. To address this, we consider what actually drove JWST costs and then assess how lessons learned from Webb could be used to assess future costs.

We performed this analysis by assessing the historical budgets, schedules, issues and risks from Webb. We surveyed lessons learned assessments developed by members of the project and got input from key system engineers from Webb. The net result of this effort and the associated analysis is the finding that there is no single metric or even a few metrics that single handedly can be linked to the cost of Webb or future missions. Since there is no single driver, there is no single "fix" that will magically and profoundly reduce mission cost. However, we did find that several challenges common to many missions collectively drove cost. These issues range from technical ones like complexity and verification to programmatic factors like funding and critical path schedule assessments. At the end of our assessment, we conclude that in order to control total lifecycle cost you have to address all of these lesson learned factors in a systematic way. We also conclude that evaluating these lessons learned can be a valuable input to assessing the cost and cost risk of future next generation large telescope decadal missions.

2. LESSONS LEARNED

The best place to start to assess the lessons learned from JWST is how the cost resources were allocated. We do this in a simplified way based on historical data in Figure 1. This chart is a projection based on 2016 data. This chart shows that no single area represents a majority of resources needed for Webb. Interestingly, the telescope element which is largely associated with aperture size alone only accounts for 15% of the total resources. However, several other considerations including the spacecraft and systems along with the instruments required even larger resources. This suggests the need to think about costs of these systems in other ways.



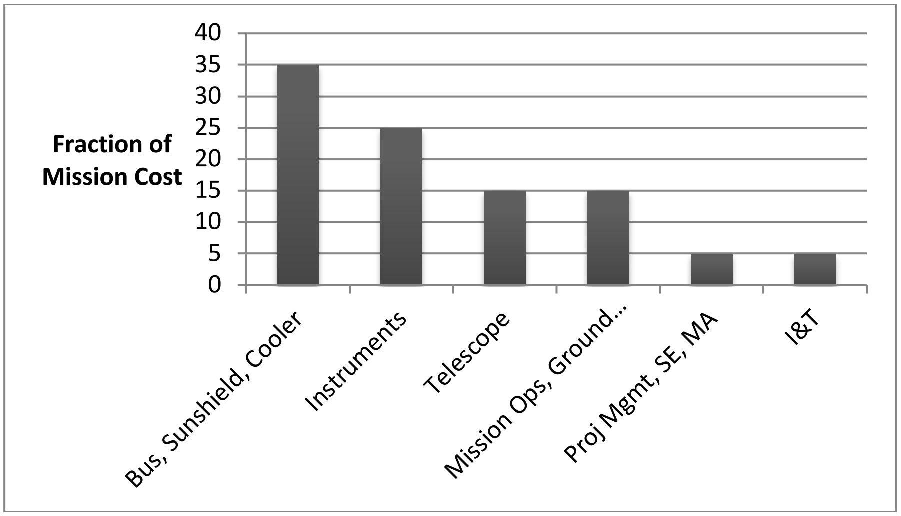


Figure 1: Webb Resource Allocation

After reviewing this distribution, we considered the actual schedules, risks, trades and issues associated with Webb to evaluate what drove the many areas shown here. We summarize the findings and lessons learned into five distinct areas:

1. System complexity (multiple difficult first of a kind challenges simultaneously, design complexity and iterations, lack of large margins)
2. Critical path and marching army considerations
3. Verification challenges (modeling, facilities, test approach)
4. Programmatic constraints (phasing, reserves, replans)
5. Early integration and test considerations (pathfinders, modularity)

Notably missing is the number of technologies which though large was not a major cost driver for Webb because the risks associated with it were largely retired early thanks to the application of lessons learned from earlier missions to invest early in these areas. Also, a subtlety of this assessment is that many of these factors interact: system complexity can drive critical path, phasing constraints can drive critical path, lack of system resources can prevent sufficient modularity, and so on. Regardless, these five areas greatly impacted the total cost for JWST and likely for future missions so we will address each of these areas in more detail.

3. SYSTEM COMPLEXITY

The first area to discuss is system complexity which in many ways impacted the other four areas. For JWST, there were several system complexity factors that led to many design iterations, complex and time consuming modeling, and to an extended set of system trades and architecture updates. By having many simultaneous challenges, it made things more time consuming and expensive. For example, being a 50 Kelvin observatory adds the complexity of needing to design and test for these temperatures with all of the material property issues (eg, CTE, damping, etc) that come with this.

The additional factor though was that Webb needed to be diffraction limited at 2um which is slightly challenging by itself but even more so when you combine it with the need to be 50 Kelvin. In many ways, these requirements along with the tight constraints on mass led to the choice of beryllium as the mirror material which was optimal for this temperature but requires more time and money for fabrication as the removal rates are slower and you have to control stresses. In addition, these combined requirements led to the need to cryo polish each mirror to remove the distortions of going cold. Had the system been diffraction limited at a longer wavelength or been warm, a faster material fabrication choice like ULE could have been usen and cryo polishing may not have been needed. Going to Beryllium also led to the need for facilitization which consumed early year resources. Making the mirrors was not the only challenge, the design of cryogenic mirrors with tight performance is also much more challenging as is verification.

Another area that drove complexity was the lack of system resources. The lack of large mass reserves drove the need for extensive lightweighting and the thermal heat dissipation margins led to extra design trades and even the addition of a deployable radiator. In both cases, large trade studies had to be undertaken to find ways to build back up margins and these then delayed the final design and consumed resources.

Another key point is the need to be lightweight with tight performance requirements also drove the need for extensive work on dealing with the effects of gravity for everything from mirrors to structures and from wavefront performance to alignment. Once the effects gravity became relevant, it required extensive modeling, model validation, and error budgets needed to accommodate this. These kinds of challenges did not occur on earlier missions like hubble which had the mass to avoid them.

Another key aspect of complexity was the fact the design was passively stable at temperature, again driven in part by both the need to be 50K and the other performance factors. Being passively stable required detailed and complex modeling with many interations and also required complex verification. The advantage of this approach was simplicity (less actuators and control authority) which would have been complicated by being cryo. However, the complex modeling led to complex models and validations like the thermal models and thermal and structural model examples shown below in Figure 2.

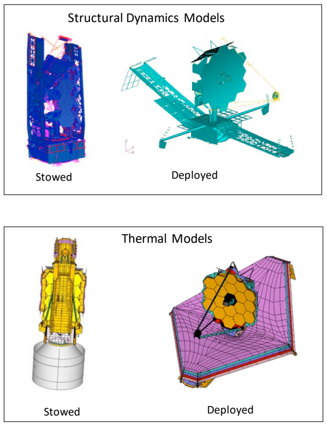


Figure 2: Model Examples

Given the challenges of complexity, a few lessons learned emerge. First, the team should focus on minimizing the number of complex challenges that are needed to do the core science. While more science is good, the cost to science curve is not linear when multiple technical challenges compound. The solution to one challenge like mass can exacerbate another challenge like gravity or thermal performance. Second, it is often the case that the architectures for missions like Webb result from a design by committee which can easily lead to more complexity to make each of the consituents happy but there needs to be strong leadership through the entire management chain to avoid too much complexity which becomes compounding.

4. CRITICAL PATH AND MARCHING ARMY

It is well known that a key to reducing costs of a program is to minimize the size of the marching army needed on the program and minimize the duration, as the cost goes with:

$$\text{Cost} = \text{Manpower} \times \text{Time (schedule)}$$

This simple adage was a major consideration for JWST and will be a major consideration for any large program because of the relatively long durations and the size of the marching army. Given this simple formula, it's critical to understand both the critical path and second critical paths as well as the size of the team.

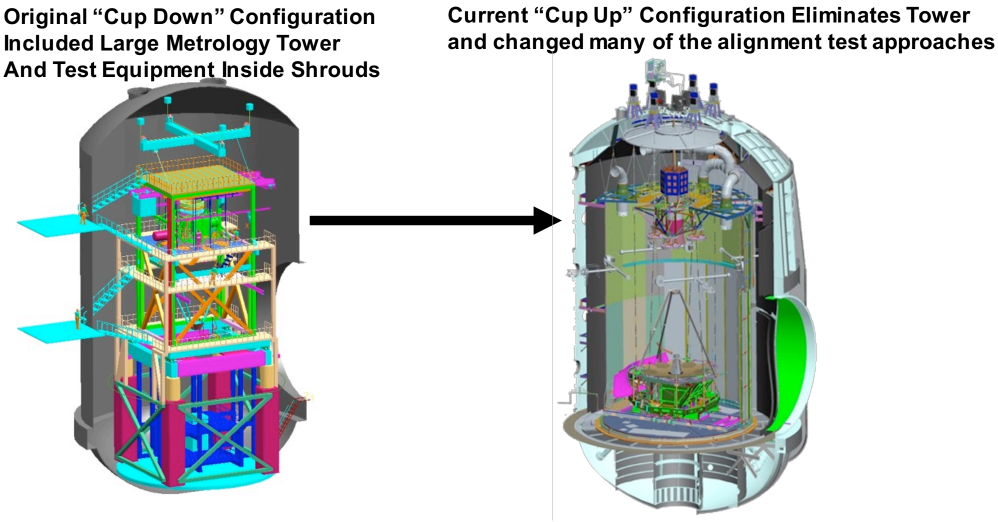
On JWST, the critical path ran through telescope and instruments for over a decade. Though the aperture size contributed to the telescope duration, the instruments were more driven by their unique combination of being cryo and tight performance specs. The cryo part drove everything from design to material selection including materials like cryo composites and beryllium which took longer to fabricate. Being cryo also drove test times. In fact, the NIRCAM instrument alone spent nearly two years in cryogenic testing. Mirror fabrication times were greatly impacted by being cryo and that fact was the key reason mirrors were made out of beryllium (beryllium has slower removal rates than glass and you have to stress relieve it periodically which takes time). It should also be pointed out that early in the development of Webb, heavy investment was made in these long lead areas but that pushed out other work which later got on the critical path.

The lessons learned here is that the critical path time needs to be factored into everything from the performance factors to the material selections to the temperatures and capabilities of the observatory if the goal is to carefully control costs. One great way to reduce time in terms of the design, facilitization time, and need for early investments to reduce durations would be to use heritage where possible which at a minimum will reduce the associated cost and schedule risk.

5. VERIFICATION CHALLENGES

Verifying a large observatory was a complex challenge for JWST because of it's size, performance and temperature along with the reliance on modeling of performance and the active nature of that system. It was also the first of a kind which drove everything from architecture iterations to facilitization. Over more than a decade, the final system architecture evolved to a point where the emphasis was on measuring what one cares about and a system that took advantage of the active nature that was optimized for cost. Making things particuarly complex was the fact that JWST is passively stable so requires modeling for model validation and of course still cares about workmanship. Beyond testing for optical alignment and wavefront performance at temperature, the team needed to address how to verify thermal performance, dynamics, and stray light for an open system which were all heavily dependent on modeling.

From a cryogenic optical test perspective, the team was able to reinvent the test architecture to address complexities in the original plans to save large costs.[iii], [iv] A great example of this was early on when the test configuration went from Cup Down to Cup Up, as shown in Figure 3, which eliminated the need for a 600,000 pound stainless steel tower that would have been very complex and lengthy to cool.



Original "Cup Down" Configuration Included Large Metrology Tower And Test Equipment Inside Shrouds

Current "Cup Up" Configuration Eliminates Tower and changed many of the alignment test approaches

Figure 3: Test Architecture Change

In some case changes were made that cost early money but which helped the verification program. For example, a pupil imaging lens and a 3-degree of freedom pickoff mirror were included in NIRCAM which greatly helped with verification of NIRCAM alignment and pupil alignment measurements but required early resources at a critical time.

As time went on, it became clear that some small additional active control in other instruments could have simplified the verification program. For example, the lack of 3-degree of freedom control in some of the science instruments coupled with the fixed tertiary meant that the alignment of the telescope to the instruments could not rely on active control and had to be verified to budgeted levels. Had there been active control, the verification would have been much simpler.

Given these examples, the lesson learned is to think about verification early, even during the achitecture phase. This may mean choosing the right levels of active control or even considering deployment strategies or thermal control strategies that are amenable to verification. While verification is required to be covered at PDR and CDR, it actually should be part of the architecture development. Fortunately for future large telescopes, there are many important lessons learned at the detailed levels of thermal and optical from JWST that can be directly applied and that is in fact being done on decadal missions. For example, on JWST it was learned to measure what you care about which meant alignment at cryo temperatures and that led to methods best suited for that (eg, photogrammetry). Future missions will not have to go through multiple iterations to verify the optical alignments of a segmented telescope but will be more driven by what is new in terms of complexity (eg, performance or system verifications). These specific lessons learned from JWST can be applied ot future active telescopes but the larger point is to focus on verification as early as possible including even in the assessment of cost. It may even be that some level of active control will strongly benefit verification and that will drive the architecture and this needs to be properly assessed in the early architecture phase. It may also be that while some systems may seem simpler, there may be new hidden verification challenges that can signficiantly drive costs.

6. PROGRAMMATIC CONSTRAINTS

Another important area is programmatic constraints which can force a program to delay funding key areas early due to fiscal phasing. JWST had single digit reserves for many of the early years and this forced the program to literally bathtub elements of the program which later in the program became the critical path.[v] The lack of early year reserves was the top issue presented in the programmtic section of the JWST Mission PDR yet the issue went on for several years.

A key lesson learned from Webb is that fiscal phasing needs to even be considered in the architecture and material choices. On Webb, the choice of beryllium required new mirror fabrication machine buildings and polishing buildings which required early year money and prevented money from being spent on other elements of the program. On future missions, the choice of mirror materials like ULE or Zerodur could allow the use of existing polishing infrastructures therebye avoiding early year money in these areas and helping avoid this issue. So fiscal funding and how those constraints play out in a realistic way needs to be considered early on and then continually.

7. EARLY INTEGRATION AND TEST CONSIDERATIONS

The final area to consider is how early integration and testing considerations can impact the entire program, especially the latter phases where marching army costs can be impacted. This means considering things like modulatiry and accessibility in the architecture. On JWST, the system complexity issues of mass and volume prevented the level of modularity that later became challenges during integration and testing. On other programs like HST, the level of modularity meant instruments or even detectors could be swapped out as issues came up or electronics boxes could be easily accessed. This issue closely relates to system complexity but the point is that considering these things early can be helpful. Interestingly, serviceability which can add some mass and complexity actually helps with integration and testing because it forces modularity and accessibility in the design phase and thus assures these things exist when needed in the latter phases.

Another really important aspect of integration and testing planning is to use Pathfinders to check out everything from ambient integration and alignment to checking out ground support equipment.

Carefully planned rehearsals of test equipment, procedures and personnel was originally a lesson from Chandra.[vi] In the case of JWST, this was highly successful for the telescope which used a pathfinder including four flight spare mirrors and three separate cryogenic tests that checked out all of the optical and thermal testing. The three pathfinder tests are summarized in Figure 4 below.

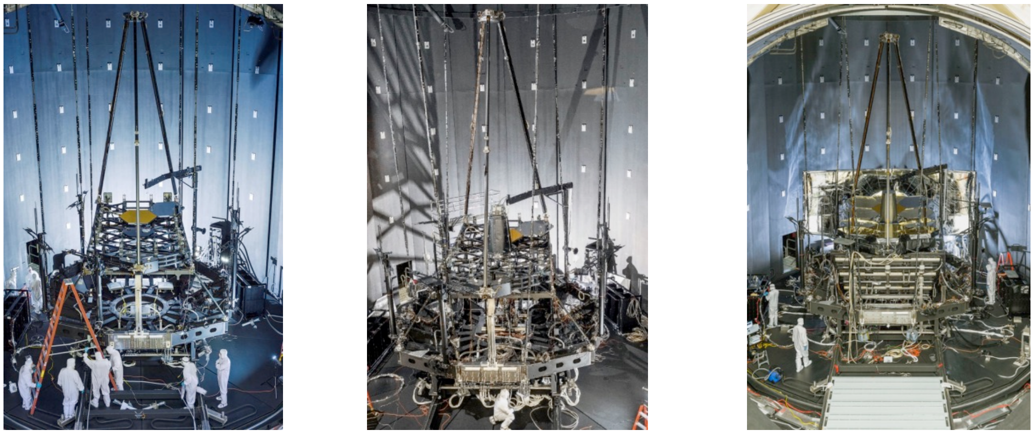


Figure 4: Three JWST Pathfinder Tests

While the JWST telescope pathfinder was very successful, as evidenced by only one telescope level cryogenic optical ultimately needed on the critical path, additional pathfinders and furthur fidelity could have been useful in other areas on JWST especially on the sunshield where lack of fidelity was an issue. This is an important lesson learned which can influence marching army costs during the integration and testing phase. It also points out that schedule and cost can be controlled when there is a well thought out pathfinder program that has the time and resources it needs from the start. In addition, a heritage based design from would reap the benefits of the pathfinder programs from JWST again saving early costs to be applied to other risks. On the other hand, a non-heritage based design may need to dedicate early resources to high fidelity pathfinders.

8. CONCLUSION

We've presented a summary of the key drivers for JWST for key resources. We've shown that to minimize costs, we need an approach that address all of the key drivers and have provided lessons learned that allows future architects and cost analysts to consider them. We contend that these five driving areas will signficiantly drive cost for large observatories. We can even envision future mission architectures get evaluated in each of these five areas based on maturity and risk and those evaluations can provide important inputs to the cost and risk assessments.

We have found that future mission studies are taking many of these lessons learned discussed here seriously early on which is good news and suggests that telescopes on the scale of JWST can be built for potentially less money than JWST.[vii] For example, the Habex and LUVOIR mission teams have resisted combining cryogenic temperatures with the need for good UV-optical performance while

OST is cold but is a longer wavelength. The teams have also made understanding verification a priority, carefully evaluated instrument suites for cost and have considered complexity in their trade discussions. In some cases, the teams have leveraged the JWST or even Thirt Meter Telescope mirror design and heritage and facilities as it makes sense which could reduce risk and save early year money. It will also allow verification and integration and test risk reductions.

What hasn't happened yet is for the cost analysts to embrace the idea of using these lessons learned areas in how they evaluate cost, perhaps even in a complementary way to the size extrapolations and mass historical database approach they may be using. Given the sample size of large telescopes is so small, using the proposed lesson learned areas to evaluate costs and risk is a potentially important and powerful tool.

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