JWST Lessons Learned

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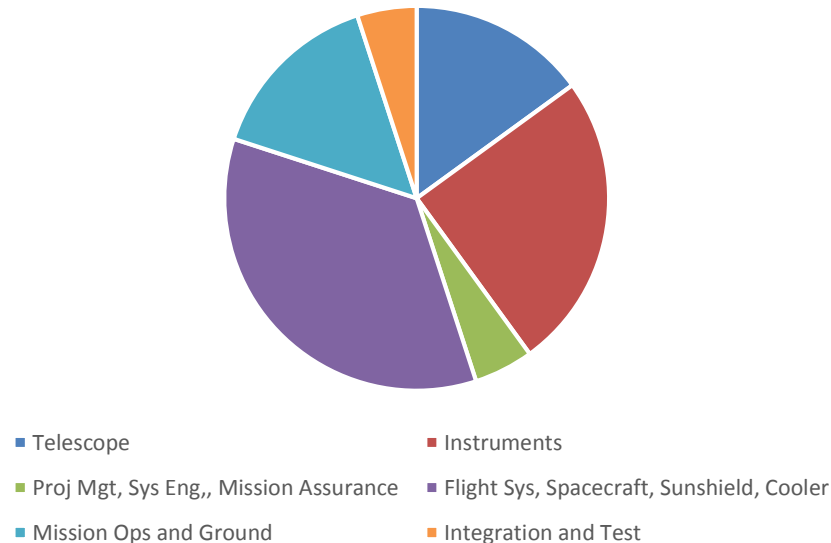
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Introduction

- While there is a lot of focus on how a few key parameters like aperture size and pixel count drive costs of large space telescopes, the JWST experience suggests that a lot more insight is needed to understand and control costs
    - Next level of detail to aperture size is how long does it take to design, fabricate, test etc. and this can be very dependent on specific requirements.
    - A smaller mirror is not necessarily cheaper!
    - Other large programs like Chandra backup this experience
- From experience on JWST, no single area drove costs, no silver bullet
- As can be seen below, the cost resources are spread across all of the WBS elements suggesting there is no single metric that can alone be correlated to costs.

Webb resource allocation

- Telescope
- Instruments
- Proj Mgt, Sys Eng,, Mission Assurance
- Flight Sys, Spacecraft, Sunshield, Cooler
- Mission Ops and Ground
- Integration and Test

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JWST lessons learned

- In thinking about what actually drove things on JWST, there are five major areas that are critical to evaluate early in the program in order to control future large telescope costs:
  - 1. System complexity (multiple difficult first of a kind challenges simultaneously, design complexity and iterations, etc.)
  - 2. Critical path and marching army driven by technical considerations (like being cryo, long manufacturing times)
  - 3. Verification challenges (modeling, facilities, test approach)
  - 4. Programmatic constraints (funding/phasing, reserves, replans)
  - 5. Early integration and test considerations (practice, pathfinders, modularity)
- Many of these factors interact: system complexity can drive critical path, phasing constraints can drive critical path, etc.
- The rest of this presentation will discuss how each of these areas impacted JWST and how we can mitigate these issues on future telescopes (eg, LUVOIR)
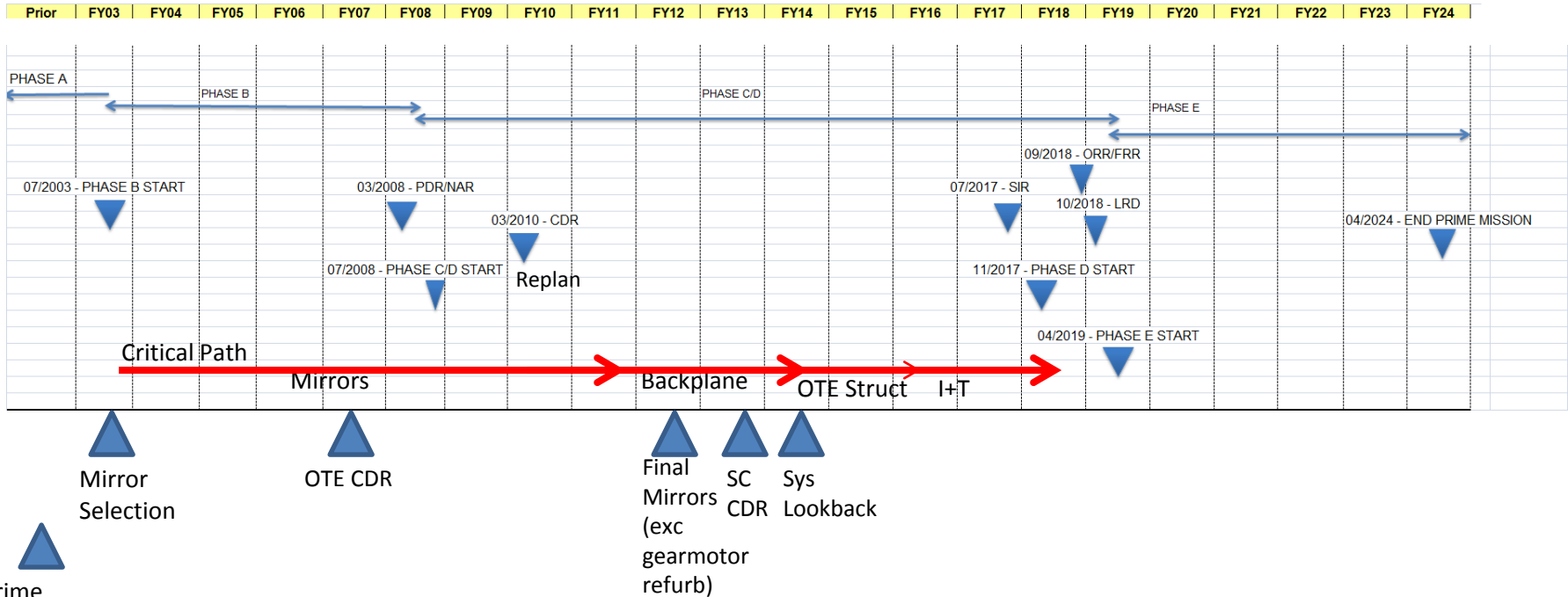
1. System Complexity

- **There were several system complexity factors that all had to be solved simultaneously leading to many design iterations, complex modeling, many system trades**
  - Cryogenic (50K) with tight performance requirements: lots of complex flexures, bond and joint complexity including cryo strength, cryo polishing while still 10's of nanometer error budgets for mirrors and stability
  - Low system margins (mass and volume) and associated programmatics
  - Lightweight structures that have to be tested in 1-g (mirrors, backplane, sunshield)
  - Large deployments, large number of single point failures, cryo shock
  - Optical quality, stability, sensitivity including MIR (thermal) and NIR (particulate)
  - Large FOV's in SI's
  - Large number of technology areas (10) – though early investment meant this was not a large driver

- Lessons Learned
  - **Focus on the minimum number of complex challenges that are needed to do the core science.**
  - **Don't architect by committee – architect by logic**
  - **Avoid short term decisions based on fiscal profiles (always consider lifecycle impacts)**

2. Critical Path and Marching Army

- A really key issue for any program is the cost associated with fixed marching army over time
  $$cost = FTE \times time \ (schedule)$$

- Schedule: JWST marching army is on board for 18 years
- Marching Army on a program like this is large
- For JWST, funding constraints meant that critical path ran through telescope and instruments for over a decade which prevented starting other areas earlier
  - While aperture size was a factor in the mirror time, the funding constraint was actually a bigger issue as it stretched things out
- In addition, facilitization was needed which ate into the same resources needed for design
- Cryo and being passive/thermal drove design times, test times on instruments and telescope

- **Lesson Learned**
  - **Prioritize schedule time and need for early resources, including: facilitization, mirror and structure fabrication times, design iterations, etc**
  - **Use heritage to save tame and reduce risk, avoid recreating the wheel when you can. Use a bigger picture strategy to design programs as a continuum.**
  - **Combining cryo and performance together is challenging.**

As-run Schedule

| Prior | FY03 | FY04 | FY05 | FY06 | FY07 | FY08 | FY09 | FY10 | FY11 | FY12 | FY13 | FY14 | FY15 | FY16 | FY17 | FY18 | FY19 | FY20 | FY21 | FY22 | FY23 | FY24 |

PHASE A

PHASE B

PHASE C/D

PHASE E

09/2018 - ORR/FRR

07/2003 - PHASE B START

03/2008 - PDR/NAR

07/2017 - SIR

03/2010 - CDR

10/2018 - LRD

04/2024 - END PRIME MISSION

07/2008 - PHASE C/D START

Replan

11/2017 - PHASE D START

Critical Path

04/2019 - PHASE E START

Mirrors   Backplane   OTE Struct   I+T

Mirror
Selection

OTE CDR

Final
Mirrors
(exc
gearmotor
refurb)

SC
CDR

Sys
Lookback

Prime
Contractor
(9/02)

NIRCAM spent 502 days in cryo testing at instrument, ISIM, OTIS level
Mirrors took 8 years to fabricate which was driven primarily by Beryllium polishing
time (Beryllium was selected because of it's cryo and performance properties)

As-run Mirror Schedule

Beryllium Chosen for Cryo Performance Took a Long Time Complete - Using up Reserve in the Early Years (opportunity cost) and stretching out marching army

Legend: L-3 SSG-Tinsley, BATC, XRCF, △ SOW Delivery, Brush Wellman, Quantum Coating, Axsys Tech, Acoustic Vibe at NGST

Beryllium Blanks

Axsys driven by machine time, stress control for Beryllium

Tinsley driven by grind and polish time and stress control of beryllium, metrology
Economies of scale helped later mirrors

Cryo Testing, metrology, actuators

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3a.   Verification Of JWST On-Orbit Performance Using Analytical Models

- **JWST is a passively stable lightweight cryo system and relies on model validation**

- **Validation:**
  - **Prove what is mathematically modeled is what was actually built**
  - **Prove interfaces are modeled correctly**

- **Building and validating models required substantial manpower, time, validation testing**

- **Correlated models, such as those on right, are used to predict/verify on-orbit performance of:**
  - **Thermal Performance**
  - **Optical Thermal Stability**
  - **Dynamics**
  - **Stray Light**

- **Tests at high levels of assembly conducted to verify "workmanship" and behavior of critical interfaces**

- ## Lesson Learned
  - **Use robust designs and active controls to minimize the reliance on complex high fidelity models**
    - **Architect the system to avoid reliance on complex modeling**
  - **Avoid complicated modeling challenges like cryo with lightweight where you can't solve it easily with robustness (cryo joints)**

Structural Dynamics Models

Stowed   Deployed
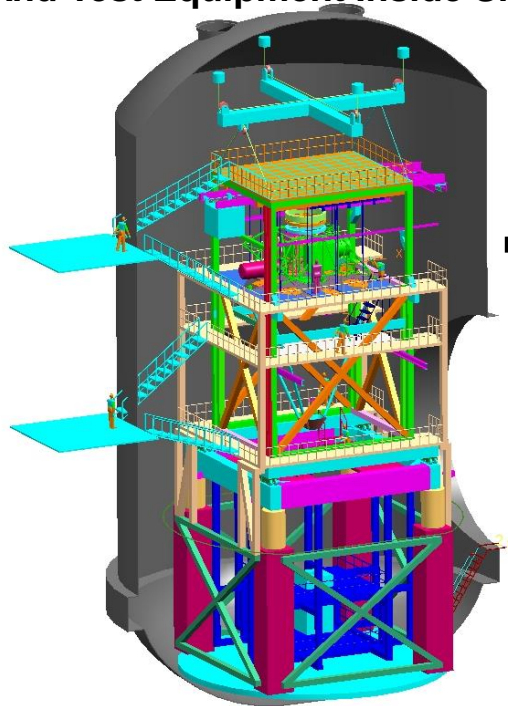

Thermal Models

Stowed   Deployed
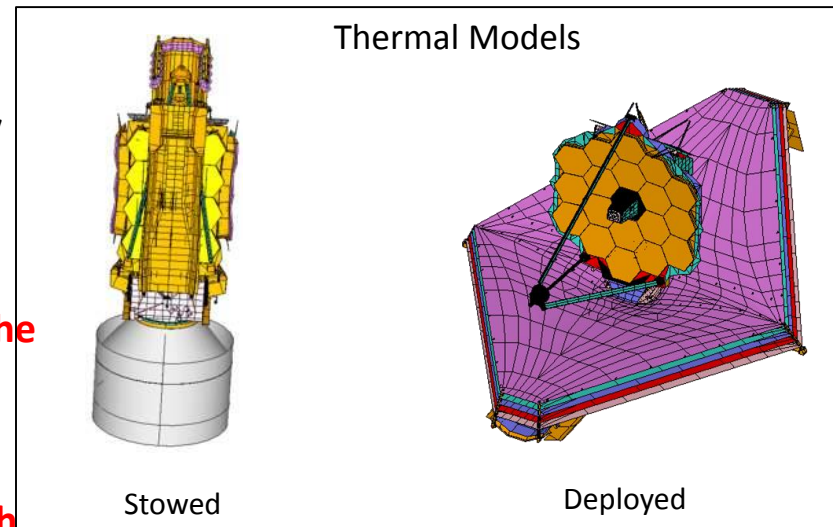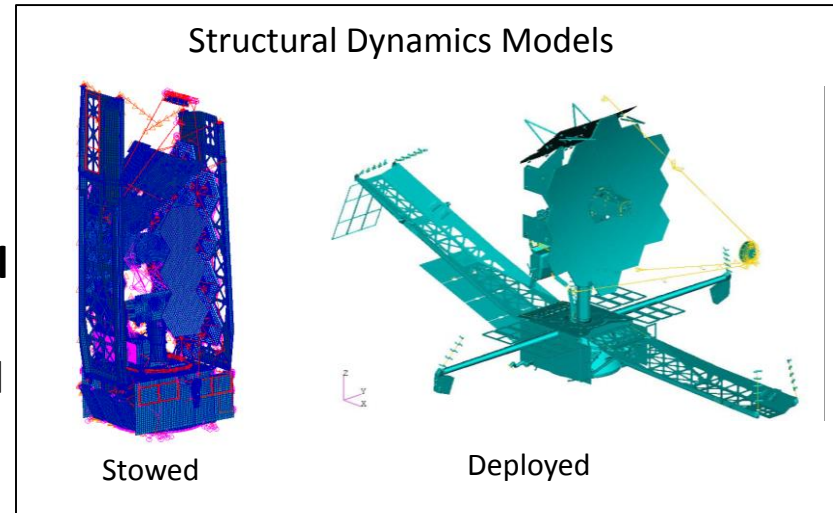
3b. Verification: System Testing

There were several iterations of the verification architecture as we got smarter on what needed to be verified and how best to do it

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
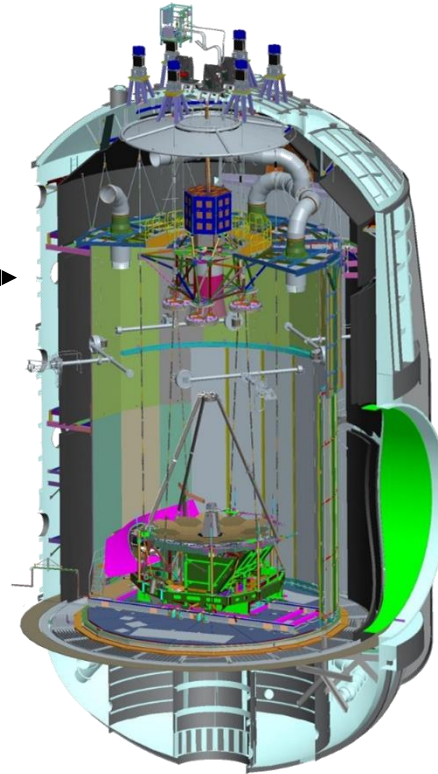
Lessons Learned:

- **Think about verification during the architecture phase**
- Consider facilities, test strategies, necessary degrees of freedom
- Use active controls as your friend.
- Measure what you need to measure

4. Programmatics/Phasing

- JWST had single digit reserves for many of the early years
  - Lack of early year reserves was the number 1 issue presented by at Mission PDR
- Had to push out work (spacecraft, mirrors, etc) due to lack of reserves
- Need for early year money for facilitization, technology maturity and complex design challenges needs to be factored against available phasing
- Lesson Learned
  - Consider facilitization time and cost as opportunity cost
  - Pick long lead items (eg, mirror and structure materials and temperatures) that don't require long design, fabrication times (eg, material removal times, economies of scale, test time)

5. Integration and testing

- Due to volume and mass constraints, some aspects of JWST are not modular:
  - Instruments installed in a sequence – doesn't allow for easy late detector swapping without removing instruments
  - Sunshield takes a long time to unfold and stow – workmanship take a long time to deal with
- Some areas of JWST had detailed pathfinders which allowed for practice and GSE checkout and greatly reduced risk, other areas did not have full scale high fidelity simulations leading to late schedule impacts
- Lesson Learned
  - Build high fidelity pathfinders to vet out integration and test processes, ground support equipment, and allow for practice
  - Strive for modularity in the design and the simplest possible interfaces including swap out of key risk items late in flow

OTIS Risk Reduction at JSC

3 Pathfinder Tests/Rehearsals in JSC Chamber to test the test equipment and ready the test team – this was highly successful! Same approach should be taken on large deployables.
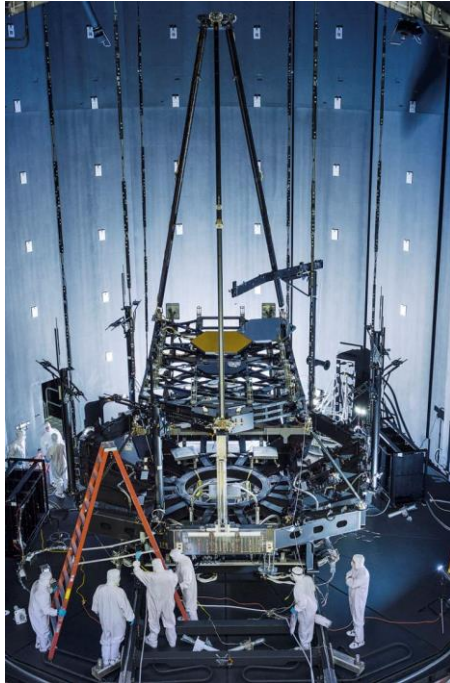
Optical Ground Support Equipment (OGSE) #1: Prove-out optical GSE. Featured Cryo Optical Test on Pathfinder OTE w/ 2 Spare PMSA's and Spare Secondary
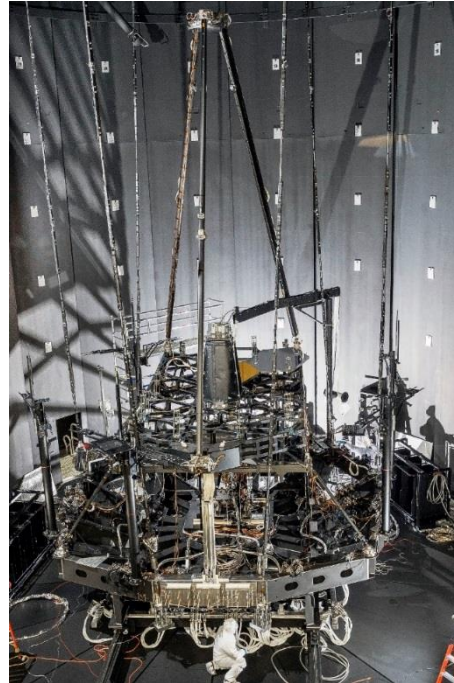
OGSE #2: 2nd Cryo Optical Test but w/ Flight Aft Optics System and AOS Source Plate Assembly. Full check-out of optical GSE and measurement schemes

Thermal Pathfinder: Verified all thermal environment/boundary conditions (e.g., sunshield layer 5 thermal simulator, ISIM radiator sinks)

Conclusions/Closing Thoughts

- To minimize costs, we need an approach that addresses the key items identified
  - Faster critical path
  - System complexity
  - Verification Approach
  - Programmatic constraints/phasing up front
  - Early integration and test considerations (practice, pathfinders, modularity)
- Several next generation architectures are taking these recommendations in consideration:
  - Not combining cryo and UV-optical
  - Leveraging heritage where it makes
  - Thinking about verification and adding in enough active controls
  - Lots of other examples
- A well thought out architecture addressing the items identified here, can make a large impact on reducing total mission cost
- The only silver bullet to controlling cost is an early and continuous disciplined, informed, systematic approach to every aspect of the program and from all layers of the program