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National Aeronautics and Space Administration

Goddard
SPACE FLIGHT CENTER

Challenges and Potential Solutions to Develop and Fund NASA Flagship Missions

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- **Introduction**
- Background – Flagship Benefits & Considerations
- Example Case Studies/Lessons Learned
  - Hubble Space Telescope (HST)
  - Mars Science Laboratory (MSL)
  - Space Interferometry Mission (SIM)
  - James Webb Space Telescope (JWST)
- A Potential New Programmatic Approach
- Summary

Introduction

- Large, Strategic “Flagship” missions have unique characteristics that lead to challenging developmental difficulties for NASA
- Missions such as the Hubble Space Telescope (HST), James Webb Space Telescope (JWST) and the Mars Science Laboratory (MSL) had technical and programmatic challenges that led to significant schedule delays and subsequent cost growth
- Although NASA has instituted policies that have reduced cost growth for more “typical” NASA science missions, NASA Flagship missions remain a distinct challenge due to their requirement to provide unprecedented science or tackle bold exploration goals
- The unique challenges presented by Flagship missions make it extremely difficult to fully predict cost and schedule given that the technical and programmatic advances needed to meet performance requirements are unprecedented
- This paper addresses why Flagship missions are unique and proposes a new programmatic approach to develop and fund Flagship missions

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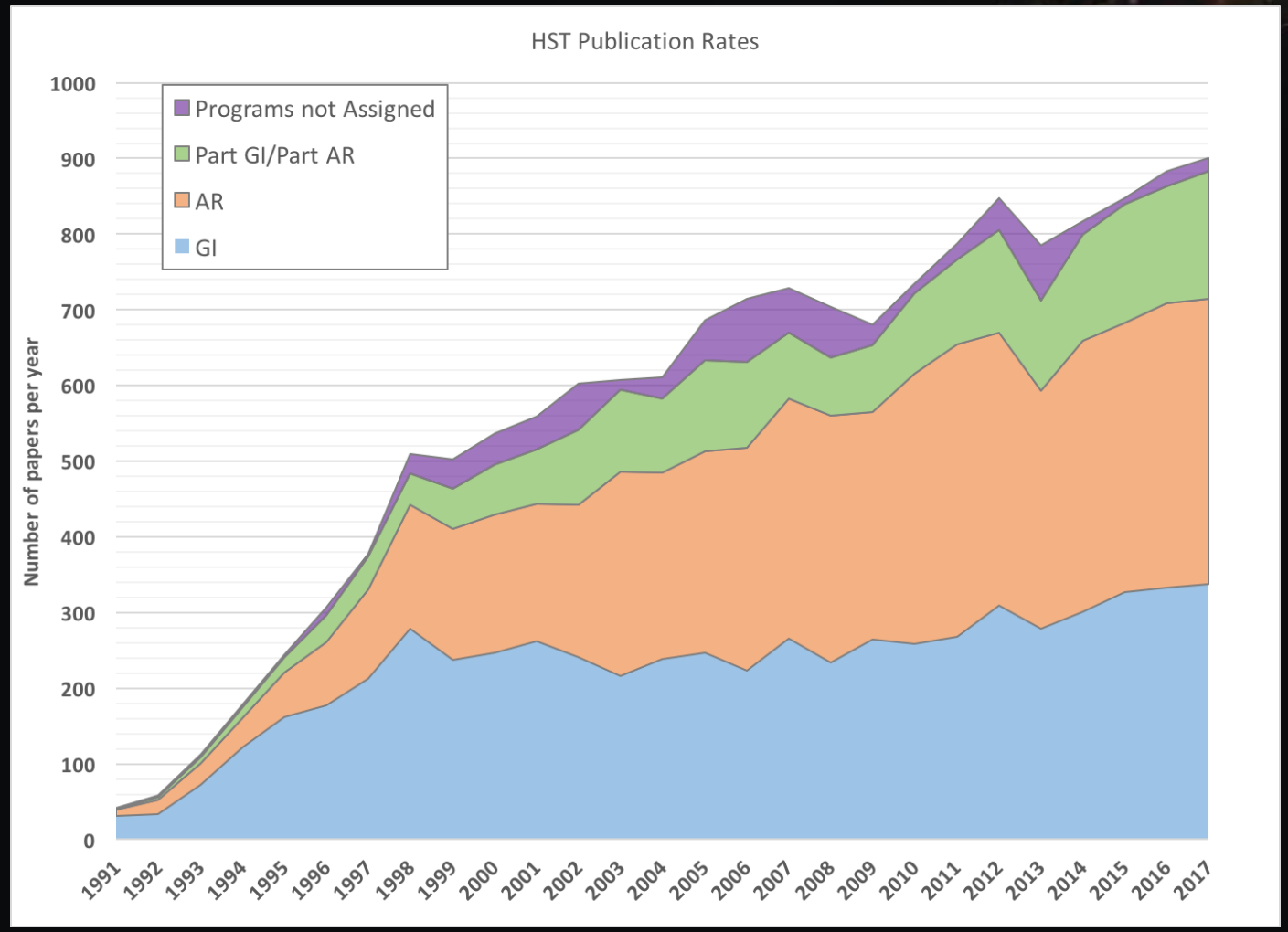
Benefits of Flagship Missions*

- Large strategic missions have multiple benefits, including:
  - Capture science data that cannot be obtained in any other way, owing usually to the physics of the data capture driving the scale and complexity of the mission
  - Answer many of the most compelling scientific questions facing the scientific fields supported by NASA's Science Mission Directorate, and most importantly, develop and deepen humanity's understanding of the Earth, our Solar System, and the universe
  - Open new windows of scientific inquiry, expanding the discovery space of humanity's exploration of our own planet and the universe, and providing new technology and engineering approaches that can benefit future small, medium-size, and large missions
  - Provide high-quality (precise and with stable absolute calibration) observations sustained over an extended period of time
  - Support the workforce, the industrial base, and technology development
  - Maintain U.S. leadership in space
  - Maintain U.S. scientific leadership
  - Produce scientific results and discoveries that capture the public's imagination and encourage young scientists and engineers to pursue science and technical careers
  - Receive a high degree of external visibility, often symbolically representing NASA's science program as a whole
  - Provide greater opportunities for international participation, cooperation, and collaboration as well as opportunities for deeper interdisciplinary investigations across NASA science areas."

Flagship missions can provide science that other missions cannot

* Note: As taken from "Powering Science: NASA's Large Strategic Science Missions", National Academies of Science, 2017

Hubble Space Telescope (HST) Publication Rates*



Hubble science has generated close to 16,000 papers over its lifetime

* Note: As taken from "https://archive.stsci.edu/hst/bibliography/pubstat.html", plot as of March 18, 2018

Flagship Assessment Findings*

- A study, conducted in 2013, identified that Flagship missions stand out from other NASA missions in terms of complexity and visibility
- The Flagship Assessment team identified several common issues affecting major mission performance:
  - A low cost and schedule estimate, sometimes referred to as buy-in, submitted by a program or project based on a number of beliefs, including optimism that the new mission can be done better (i.e., faster, cheaper) than previous missions, the notion that new techniques will improve cost and schedule performance, the desire on the part of those external to NASA for the Agency to find ways to do more work at a lower cost, experience that says changes will happen regardless of the robustness of the project's plan, or a desire to win a competitive bid for the next new mission
  - Inadequate funding for concept studies, concept and technology development
  - Changes in requirements, funding profiles, workforce, and partner contributions throughout development, even after the Agency has committed to mission content, cost and schedule
  - Technical challenges, mission complexity or the number of new technologies needed for the mission to succeed
  - Disconnects with the external budget environment or changes in the political environment
  - Differences between Agency and stakeholder priorities where NASA prioritizes mission success and other stakeholders set delivering a mission on cost and schedule as an equal priority

Flagship missions are unique and have different issues than other NASA missions

* Note: As taken from Cost and Schedule Growth in NASA Missions: Findings and Recommendations from the Explanation of Change Study and Flagship Mission Assessment", Office of the Center Director, Goddard Space Flight Center, 2013

Many Large Projects Incur Cost Growth

- Projects with Significant Complexity
  - The cost to find Higgs boson was $13.25B for the Large Hadron Collider (LHC) and experiments while the LHC costs about $1B a year to keep operating. The initial cost of the LHC plus experiments was supposed to be on the order of 2.8B Swiss francs and ended up being around 5.8B. It was supposed to be built in
    7 years and took 10 years to finish (and needed another year to become operational after a magnet quench incident)
  - The Superconducting Super Collider (SSC) was originally supposed to cost $4.4B and was estimated to be $11B when it was cancelled after 6 years of development and over $2B spent
- Projects with Significant Prior Knowledge
  - The latest Gerald R. Ford aircraft carrier (commissioned in 2015) cost $13B, which took 10 years to develop, which was 3 years behind schedule and $2.4B over cost (the USN has been building aircraft carriers since prior to WW2)
  - The “Big Dig” cost $14.6 billion relative to the original project cost estimate of $2.6 billion and was originally scheduled to take 4 years vs. the 10 year actual
  - The Chunnel was proposed at $5.5B and cost $14.6B
  - McKinley Consulting recently did a study that looked at over 60 different construction projects in the mining, infrastructure, and oil & gas industries and stated that the average cost overrun was 80% and they were delivered 2 years later than promised (the Egyptians built infrastructure projects (i.e., the pyramids) in 2500 B.C.!)

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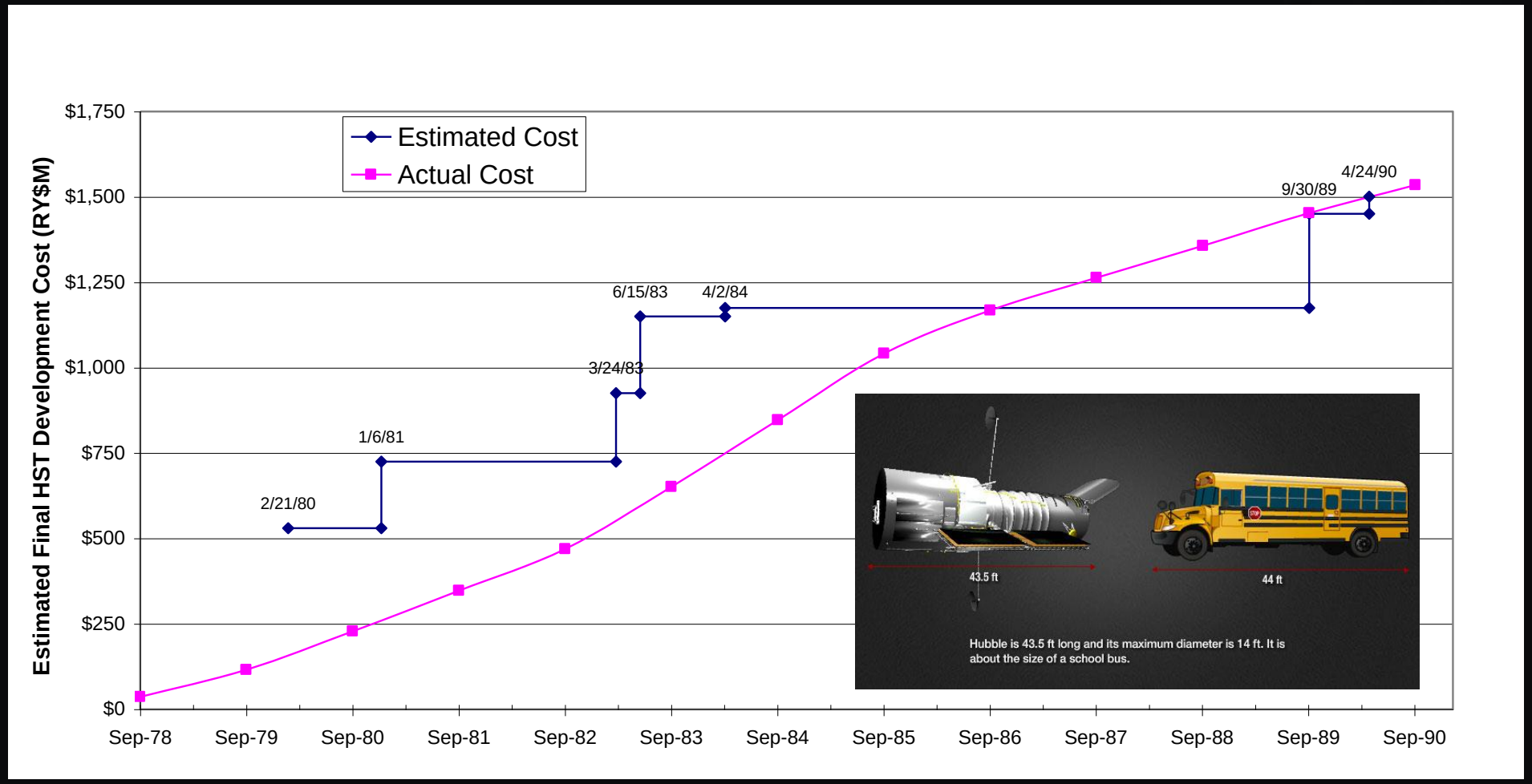
Flagships Push the Envelope of Scientific Discovery

- Flagship missions typically provide unprecedented science which requires unprecedented complexity relative to the state of the art
- Some examples include
  - Hubble Space Telescope (HST)
    - Largest space-based telescope ever launched
    - Developed to be serviceable for planned 17-year operational life
  - Mars Science Laboratory (MSL)
    - Controlled landing of a Mini-Cooper sized within
    - Unprecedented sample acquisition and analysis covering a wide range of samples
  - Space Interferometry Mission (SIM)
    - 2 orders of magnitude improvement in astrometric precision compared to historical system
  - James Webb Space Telescope (JWST)
    - Largest telescope ever put into space operating at cryogenic temperatures
    - Most complex system ever tested and put in orbit

HST Actual and Estimated Cost Growth History

*Comparison of HST Estimated vs. Actual Cost**

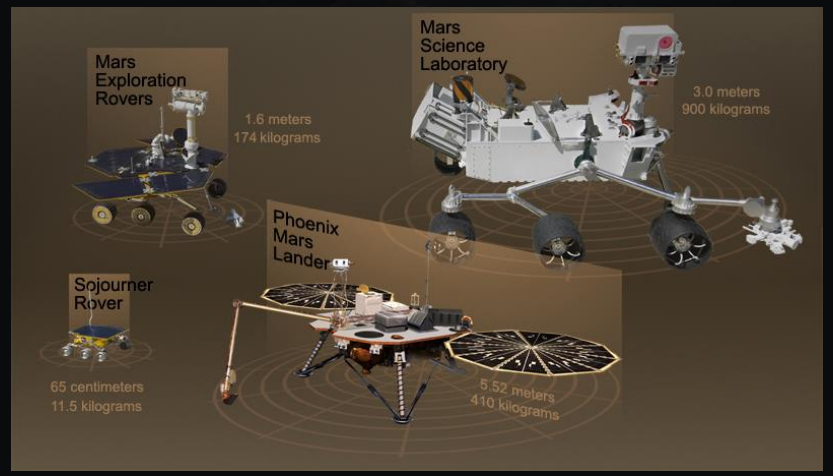


* Note: As taken from NASA Historical Data Book, Volume 5

HST cost growth can be attributed to underestimating the development difficulty

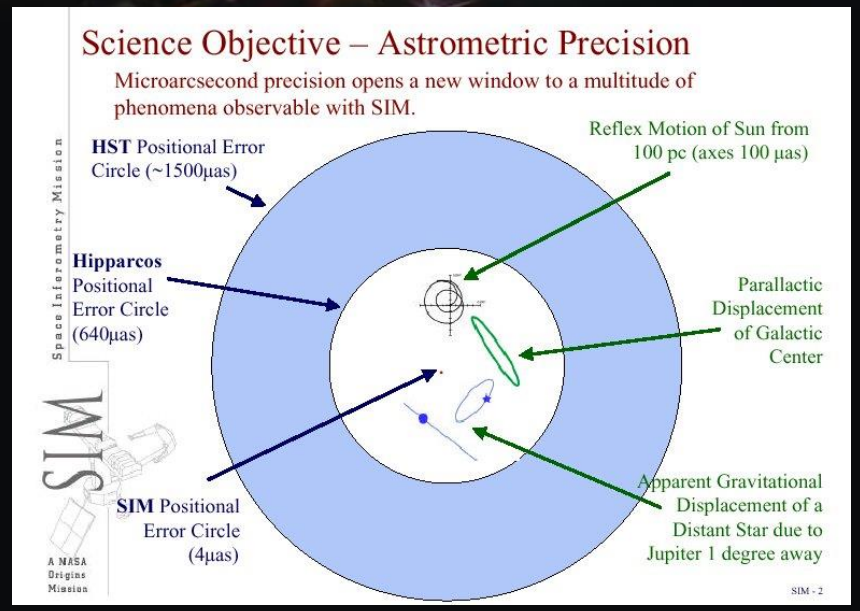
MSL Case Study

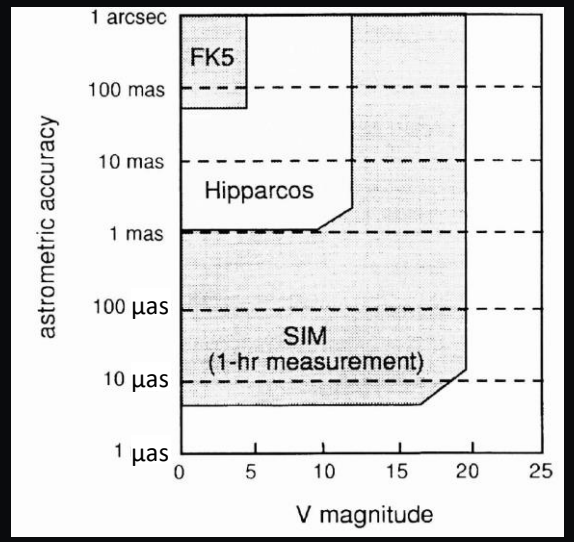
- Background
  - Landing of largest Mars rover required development of descent module (Sky Crane), complex instruments, and new mechanisms to operate in cold temperatures
- Development Cost & Schedule Performance (from NASA Budget Data)
  - Decadal Cost Estimate: <$650M in 2003 Decadal
  - Initial development cost & schedule: $1.7B FY17$B, 4 year development schedule
  - Final development cost & schedule: $2.7B FY17$B, 6 year development
- Challenges that occurred
  - Overall system complexity required to meet mission requirements
  - Funding profile was back loaded which was inconsistent with development requirements
  - Missing planned launch window resulted in 2-year delay until next window opened



SIM Case Study

- Background
  - Provide 2 orders of magnitude improvement in astrometric precision relative to the European Space Agency's Hipparcos mission in order to find Earth-like planets
- Development Cost & Schedule Performance
  - 1990 Decadal Cost Estimate: $250M (known as the Astrometric Interferometry Mission)
  - 2010 Decadal Cost Estimate: $1.9B
  - Cancelled after 10 years technology development
- Technological challenges that occurred
  - Nanometer level control & stabilization of optical elements on a lightweight flexible structure
  - Sub-nanometer level sensing of optical element relative positions over meters of separation distance
  - Overall instrument complexity and the implications for interferometer integration and test and autonomous on-orbit operations





Cancellation of SIM

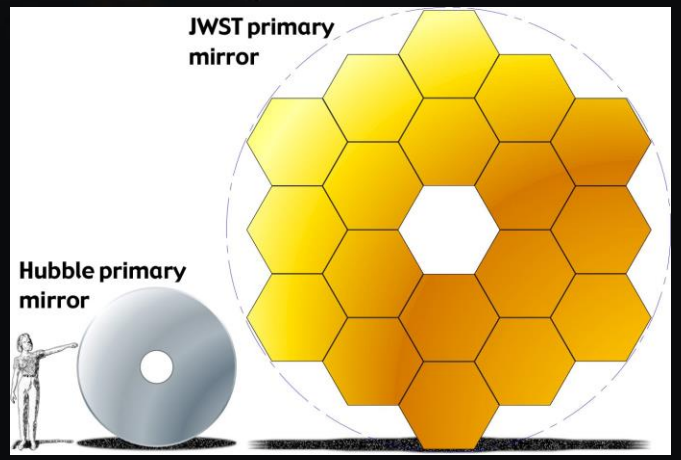
- From "New Worlds, New Horizons in Astronomy and Astrophysics", Committee for a Decadal Survey of Astronomy and Astrophysics, National Academies Press, 2010
  - SIM (SIMLite in 2010) … not included in the recommended program for the decade, following the committee's consideration of the strengths of competing compelling scientific opportunities and the highly constrained budget scenarios described in this report.
  - SIMLite is technically mature and would provide an important new capability (interferometry). Through precision astrometry it could characterize the architectures of 50 or so nearby planetary systems, provide targets for future imaging missions, and carry out other interesting astrophysics measurements. However, the committee considered that its large cost (appraised by the CATE process at $1.9 billion from FY2010 onward) and long time to launch (estimated at 8.5 years from October 2009)
- SIM Expenditures prior to Cancellation

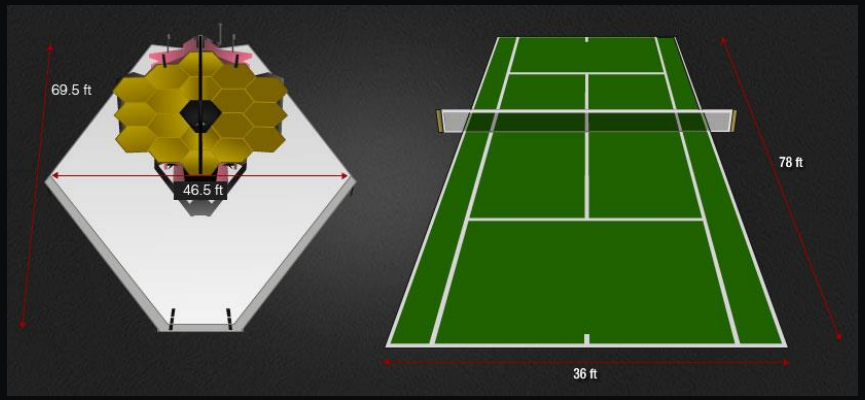
	FY99	FY00	FY01	FY02	FY03	FY04	FY05	FY06	FY07	FY08	Total
SIM	$ 34.2	$ 39.2	$ 29.7	$ 37.7	$ 42.3	$ 87.9	$ 101.5	$ 115.0	$ 100.6	$ 21.6	$ 609.7

- SIM experience showed that the process worked, i.e., that technology development was required before mission development began
  - Unfortunately other missions took priority over SIM
  - Money spent on technology development, however, was useful to other future missions

JWST Case Study

- Background
  - Most complex space-based observatory ever developed requiring significant technology development to operate at cryogenic temperatures
- Development Cost & Schedule Performance (from NASA Budget Data)
  - Decadal Estimate: $1.2B, 5 years tech development + 5 years production
  - Initial development cost & schedule: $2.3B FY17$B, 8 years (Delta MDR)
  - Final development cost & schedule: $TBD FY17$B, 20 years
- Challenges that occurred
  - Mirror development, sunshield deployment, cryocooler development
  - Mandated funding led to poor early development decisions
  - Funding profile restricted in early years led to delay in development for future years





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Flagship Mission Funding Approach

- Flagship pushes against the limit NASA lifecycle paradigm and should be examined differently
  - Technology development issues
  - Overall System Complexity
  - Size of Investment (>$2B)
  - Multiple organizations/partners
- Potential different funding approaches
  1. Put a number out early that can't be substantiated
     - "Guess and go" is not a good management strategy
  2. Put out a low number and wait until the last minute
     - "Low ball" isn't good for public support or Project Manager longevity
  3. Work technology development and mature concept before putting together final cost of mission
     - Best estimate but limited US Government commitment
  4. Same as 3 except ask Congress for Full Funding
     - Best estimate with commitment over multiple administrations

Flagship Funding–New Programmatic Approach

New Programmatic Approach

Step 1: Conduct a science assessment and concept feasibility study to determine the value of the science and define technology challenges

Step 2: Fund technologies to TRL 6 with defined pass/fail gates for each technology where the phase is open ended with a consistent level of technology funding until technologies pass the required TRL gate

Step 3: Begin an open-ended Phase B to mature the whole system concept to TRL 6 by PDR, include prototyping of manufacturing and test activities

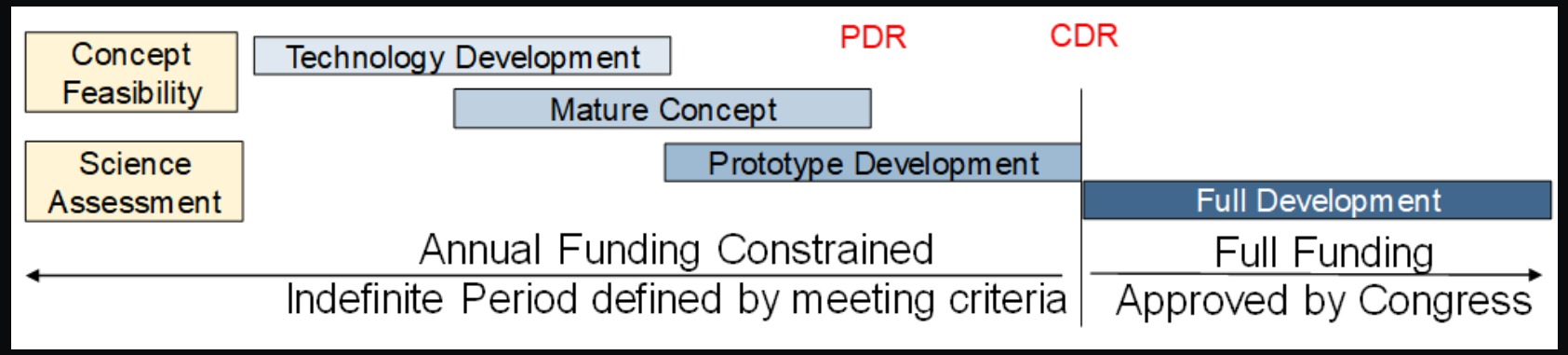
Step 4: Agree to a not-to-exceed annual funding level that continues until a prototype is complete (Step 6)

Step 5: After the technology development phase is complete, develop a prototype of the system to work out implementation issues to know the scope of work going forward

Step 6: As prototype development is nearing completion, provide a realistic estimate of the scope of work ahead using CDR as the gate for continuation

Step 7: Get Congressional approval for all remaining development funds which is similar to working capital funds for the U.S. Navy for aircraft carrier procurement

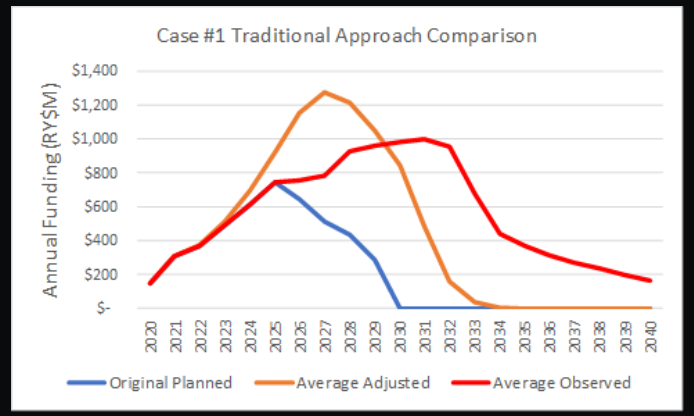
Step 8: Conduct Phase C/D as typical, holding the Systems Integration Review (SIR), Pre-Environmental Review (PER), Pre-Ship Review (PSR), etc., with lower level peer reviews as needed



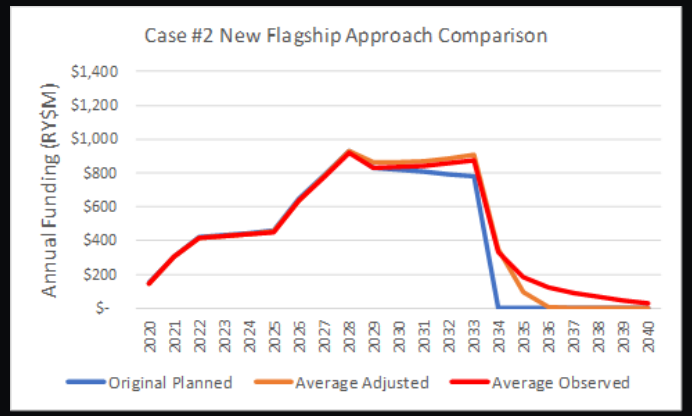
Sand Chart Tool (SCT) Analysis Results

SCT utilized to assess if proposed approach is beneficial

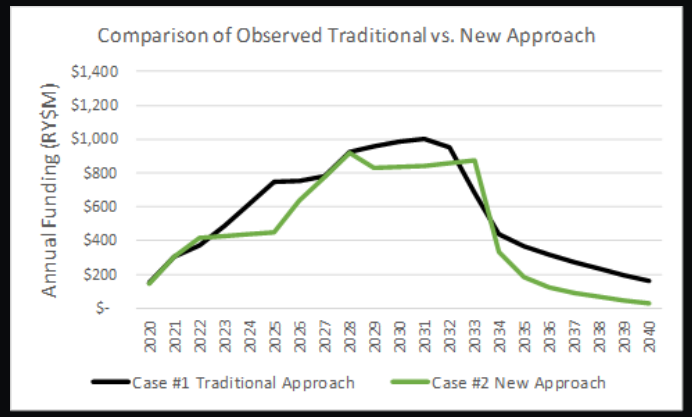
Case #1 Traditional Approach:
Early, Low Estimate with Overruns



Case #2 New Flagship Approach:
Estimate after CDR mature design



Comparison of Profiles



Comparison of Results

Case #1 Traditional	Original Planned	Simulation Observed
Launch Date	March 2029	May 2035
Cost (FY$20)	$4.0B	$9.5B

Case #2 New Approach	Original Planned	Simulation Observed
Launch Date	March 2033	January 2034
Cost (FY$20)	$7.0B	$7.7B

Providing early development funding with longer development period provides more mature design and programmatic baseline combined with full funding for proposed Flagship approach

Flagship Considerations

- US Navy Aircraft Carriers (literally a Flagship) are fully funded through a working capital fund so that USN doesn't have to be concerned with changes in annual budgets or changes in Administration as Congress approves once and the national asset is built
  - NASA Flagship missions should be considered as a similar national asset
- Full funding is not new to NASA as the Space Shuttle Endeavour was funded in this manner
- When NASA Flagship programs defer work because of the constrained annual funding requirements, they are typically in weakened positions downstream in their development, and are faced with an inexecutable "bow wave" of deferred work
  - The GAO review of the Orion program noted NASA's practice of deferring work due to constrained budgets leading NASA and Lockheed Martin to delay the development of select systems
- The Office of Management & Budget (OMB), General Accounting Office (GAO) and The RAND Corporation all identify benefits with fully funding large scale projects

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- NASA Flagship missions are unique in terms of their consistent attempt to push the boundaries of scientific discoveries by orders of magnitude above previous missions
- These missions provide substantial benefits to the science community as well as to the prestige of NASA
- This challenge typically requires technology and engineering developments that are often first-of-a-kind such that predicting the cost and schedule of these missions is difficult. Because of these unique circumstances, the approach to developing NASA Flagship missions should be unique
- The paper proposed a way in which annual funding is provided in the early stages of development, to cover feasibility studies, technology developments, and prototype development, before fully funding the Flagship mission for the remaining development
- The proposed approach should allow for a full assessment of the benefits of a given Flagship mission while having a firm grasp on the cost prior to fully committing to the mission