Perspectives on NASA Mission Cost and Schedule Performance Trends

Presentation for the Future In-Space Operations (FISO) Colloquium

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Acknowledgments: Claude Freaner, Dave Bearden, Debra Emmons, Tom Coonce
Typical Questions

- What is the magnitude of cost and schedule growth?
  - How reliable are projects’ estimates in the conceptual design stage?
  - Why does cost growth occur?
  - What is the relationship between cost, schedule and “complexity”?
  - Are there any improvements that can be made in estimating the costs of future design concepts?
Forty NASA Robotic Science Missions Experienced 27% Cost and 22% Schedule Growth*

* “Using Historical NASA Cost and Schedule Growth to Set Future Program and Project Reserve Guidelines”, Bitten R., Emmons D., Freaner C.
While Significant Variability is Evident, for Every 10% of Schedule Growth, there is a Corresponding 12% Increase in Cost*

\[ \%\text{Cost Growth} = 1.2348 \times \%\text{Schedule Growth} \]

\[ R^2 = 0.6124 \]

* “Using Historical NASA Cost and Schedule Growth to Set Future Program and Project Reserve Guidelines”, Bitten R., Emmons D., Freaner C.
Comparison of Schedule Growth Data with Agency Guidelines: NASA Telescope Missions

Four of Six Telescope Missions Exceeded Common Schedule Reserve Guidelines

Growth shown is above planned schedule reserve

NASA/JPL Guidance
1.8 Month per Year

General Rule of Thumb
1 Month per Year
Comparison of Schedule Growth and Success for Planetary Missions vs. Earth-orbiting Missions*

- Development times for Planetary missions less than Earth-orbiting missions due to constrained launch windows
- Planetary missions experienced less schedule slip on average than earth-orbiting missions
- However, planetary missions failed or impaired twice as often

<table>
<thead>
<tr>
<th>Sample Size</th>
<th>Planetary</th>
<th>Earth-Orbiting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schedule Growth</td>
<td>3.9%</td>
<td>38.3%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Planetary</th>
<th>Earth-orbiting</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Successful</td>
<td>30%</td>
<td>84%</td>
</tr>
<tr>
<td>% Partial</td>
<td>40%</td>
<td>7%</td>
</tr>
<tr>
<td>% Catastrophic</td>
<td>30%</td>
<td>9%</td>
</tr>
</tbody>
</table>

Typical Questions

- What is the magnitude of cost and schedule growth?

- How reliable are projects’ estimates in the conceptual design stage?

- Why does cost growth occur?

- What is the relationship between cost, schedule and “complexity”?

- Are there any improvements that can be made in estimating the costs of future design concepts?
Ten Missions Demonstrate How Accuracy of Project Estimates Increases Over Time however Cost Growth, Over and Above Reserves, Still Occurs Deep into the Project Life Cycle
In What Phase Does Cost Growth Occur?

Greatest Growth Occurs During Integration and Test (Phase D) When Trying to Get Hardware & Software to Function as Designed
Typical Questions

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• Why does cost growth occur?

• What is the relationship between cost, schedule and “complexity”?

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Some of the Reasons

• Inadequate definition of technical and management aspects of a program prior to seeking approval
  
  (NASA’s Project Management Study, 1980)

• Program and funding instability; difficulties in managing programs in an environment where funding must be approved annually and priorities change
  
  (Advisory Committee on the Future of the U.S. Space Program, 1990)

• Lack of emphasis on technological readiness and requirements on the front end of a program
  
  (NASA’s Roles and Missions Report, 1991)

• Program redesign, Technical Complexity, Budget Constraints, Incomplete Estimates
  
  (GAO Report on NASA Program Costs, 1992)
The Reasons for Growth - Study of 40 NASA Missions: Internal versus External Factors Driven-Growth*

- **Internal Growth** (within Project’s control)
  - Technical
    - Spacecraft development difficulties
    - Instrument development difficulties
    - Test failures
    - Optimistic heritage assumptions
  - Programmatic
    - Contractor management issues
    - Inability to properly staff an activity

- **External Growth** (outside Project’s control)
  - Launch vehicle delay
  - Project redesign
  - Requirements growth
  - Budget constraint
  - Labor strike
  - Natural disaster

* “Using Historical NASA Cost and Schedule Growth to Set Future Program and Project Reserve Guidelines”, Bitten R., Emmons D., Freaner C.
Mass Growth Exceeds Typical Guidance*

- Average mass growth for ten missions studied is 43% which exceeds the typical industry guidelines of 30% mass reserves (over CBE) at the start of Phase B

Assessing Relationships for Causality: 
Inherent Optimism in Initial Design & Estimates*

Progression of Average Cost Growth for Discovery Selections May be Indicative of Competitive Pressures Leading to More Aggressive Designs

* "Using Historical NASA Cost and Schedule Growth to Set Future Program and Project Reserve Guidelines", Bitten R., Emmons D., Freaner C.
Typical Questions

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Hypothesis*

- **Complexity Index** could be derived using a broad set of parameters to arrive at a top-level representation of the system.
- Correlation to spacecraft cost and/or development time based on actual program experience might be apparent.
- Data assembled for most spacecraft launched during past two decades (1989 to present) including technical specifications, costs, development time, mass properties and operational status.
- Complexity Index calculated based on performance, mass, power and technology choices for purposes of comparison.
- Relationship between complexity and “failures” investigated compared with adequacy of cost and schedule resources.
- Method to assess complexity at the system-level should allow more informed overall decisions to be made for new systems being conceived.


Illustrations reprinted courtesy of NASA
### Complexity Index Example

<table>
<thead>
<tr>
<th>Factor</th>
<th>Unit</th>
<th>Min</th>
<th>Mean</th>
<th>Max</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload Mass</td>
<td>(kg)</td>
<td>0</td>
<td>265</td>
<td>6065</td>
<td>90</td>
</tr>
<tr>
<td>Payload Orbit Average Power</td>
<td>(W)</td>
<td>0</td>
<td>166</td>
<td>1600</td>
<td>62</td>
</tr>
<tr>
<td>Payload Peak Power</td>
<td>(W)</td>
<td>0</td>
<td>174</td>
<td>750</td>
<td>85</td>
</tr>
<tr>
<td>Payload Data Rate (average)</td>
<td>(Kbps)</td>
<td>0</td>
<td>11678</td>
<td>304538</td>
<td>175</td>
</tr>
<tr>
<td>Number of Instruments</td>
<td></td>
<td>1</td>
<td>4</td>
<td>18</td>
<td>3</td>
</tr>
<tr>
<td>Aperture diameter</td>
<td>(cm)</td>
<td>3</td>
<td>67</td>
<td>240</td>
<td>60</td>
</tr>
<tr>
<td>BOL Power</td>
<td>(W)</td>
<td>12</td>
<td>761</td>
<td>8000</td>
<td>1750</td>
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<tr>
<td>EOL Power</td>
<td>(W)</td>
<td>3</td>
<td>653</td>
<td>6600</td>
<td>1651</td>
</tr>
<tr>
<td>Solar Array Area</td>
<td>(m²)</td>
<td>0</td>
<td>5</td>
<td>58</td>
<td>7.5</td>
</tr>
<tr>
<td>Solar Cell Type/Power Source</td>
<td></td>
<td>Si</td>
<td>GaAs, GaAs-mult</td>
<td>GaAs-conc, RTG/R</td>
<td>GaAs-mult</td>
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<tr>
<td>Battery Type</td>
<td></td>
<td>Lead-acid</td>
<td>NiCd, SNiCd</td>
<td>NiH2, Li-Ion</td>
<td>Li-Ion</td>
</tr>
<tr>
<td>Battery Capacity</td>
<td>(A-hr)</td>
<td>1</td>
<td>36</td>
<td>516</td>
<td>266</td>
</tr>
<tr>
<td># Articulated Structures</td>
<td></td>
<td>0</td>
<td>1</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td># Deployed Structures</td>
<td></td>
<td>0</td>
<td>2</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>Number of Thrusters+Tanks</td>
<td>(#)</td>
<td>0</td>
<td>4</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>Max Uplink Data Rate</td>
<td>(kbps)</td>
<td>0</td>
<td>38</td>
<td>2000</td>
<td>2.0</td>
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<tr>
<td>Transmitter Power (peak)</td>
<td>(W)</td>
<td>1</td>
<td>10</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>Central Processor Power</td>
<td>(Mips)</td>
<td>0</td>
<td>58</td>
<td>1600</td>
<td>119</td>
</tr>
<tr>
<td>Onboard Software Code</td>
<td>(KSLOC)</td>
<td>2</td>
<td>78</td>
<td>650</td>
<td>110</td>
</tr>
<tr>
<td>Flight Software Reuse</td>
<td>(%)</td>
<td>0%</td>
<td>36%</td>
<td>90%</td>
<td>47%</td>
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<tr>
<td>Data Storage Capacity</td>
<td>(Mbytes)</td>
<td>0</td>
<td>4186</td>
<td>136000</td>
<td>512.0</td>
</tr>
<tr>
<td>Thermal Type</td>
<td></td>
<td>passive-heaters, semi-active</td>
<td>active, cryo-heaters</td>
<td>single-sc</td>
<td>25%</td>
</tr>
<tr>
<td>Multi-Element System?</td>
<td></td>
<td>CL, mult (aerobr, rend)</td>
<td>entry/landed/dock</td>
<td>mult</td>
<td>66%</td>
</tr>
</tbody>
</table>

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**Complexity Index** 60%

**Normalized Complexity Index** 79%
When is a Mission Too Fast?*

**Schedule as Function of Complexity**

\[ y = 20.084e^{1.7203x} \]

\[ R^2 = 0.7165 \]

When is a Mission Too Cheap?*

Development Cost as Function of Complexity

\[ y = 5.6931e^{5.9893x} \]

\[ R^2 = 0.8973 \]

3-D Trade Space – Intuitive Result: Missions that have the greatest complexity, are highest cost and longest development*

Complexity Bands vs. Cost and Schedule Help Proposers
Define Scope of Mission to Fit Fixed Cost & Schedule*

NASA’s Report Card Following Mars ’98 Failures

• Complexity of Failed Missions High in Both Catagories!
• Planetary Missions are “Fastest”
  – But fail more often than earth-orbiters
• NASA Earth-Orbiting Missions are “Cheapest”
  – But longer to develop than planetary
• Overall Success Record is About 3 out of 4!

<table>
<thead>
<tr>
<th></th>
<th>NASA Planetary</th>
<th>NASA Earth Orbiting</th>
<th>All NASA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Complexity</td>
<td>94%</td>
<td>91%</td>
<td>93%</td>
</tr>
<tr>
<td>of Failed/Impaired</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Missions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Complexity</td>
<td>70%</td>
<td>55%</td>
<td>58%</td>
</tr>
<tr>
<td>of Successful Missions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall Average</td>
<td>82%</td>
<td>60%</td>
<td>67%</td>
</tr>
<tr>
<td>Complexity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Success Ratio: &quot;Better&quot;</td>
<td>50%</td>
<td>86%</td>
<td>74%</td>
</tr>
<tr>
<td>Average Development</td>
<td>41</td>
<td>46</td>
<td>44</td>
</tr>
<tr>
<td>Time: &quot;Faster&quot; (mos)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Spacecraft Cost</td>
<td>132</td>
<td>75</td>
<td>98</td>
</tr>
</tbody>
</table>

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For a project that has fixed requirements and schedule, the inevitable outcome is that cost will grow if developmental problems occur.

Case Study: Mars Exploration Rover (MER)
- 90-day surface lifetime; ~9-mos cruise
- Launch Mass: 1050 kg (Delta II)
- Mobile platform: 1000-m range

Assessment found that:
- 33-month development appeared inadequate
- “Open Checkbook” and heritage offset shortfall

Mitigations:
- Focused on rapidly deploying staff to front load schedule (dual/triple shifts)
- Developed extra hardware test-beds

Cost grew from $299M to $420M

Can $$$ Buy Time?
Complex rovers were developed in a dangerously short period

The Mars Exploration Rovers are complex spacecraft developed under a tight schedule, a classic recipe for disaster. NASA is fully aware of this and unlike the agency’s prior “Faster, Better, Cheaper” philosophy, is now willing to throw money at the problem. Today’s tune might be called “Tester, Better” but not “Cheaper.”

The shortage of time is apparent in a comparison made by The Aerospace Corp. This technique was reported by Aviation Week & Space Technology 2000 and has been updated to include Mars Exploration Rovers (MERs) and other programs. (AW&ST June 12, 2000, p. 47). The method assigns MER a Complexity Index of 0.81, on a scale where 1.0 is the most complex space.
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Example: Substantial Differences Exist between STEREO Science Definition Team (SDT) and Final Implemented Configuration*

<table>
<thead>
<tr>
<th></th>
<th>SDT</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Programmatics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schedule (months)</td>
<td>40</td>
<td>70</td>
</tr>
<tr>
<td>Launch Vehicle</td>
<td>Taurus</td>
<td>Delta II</td>
</tr>
<tr>
<td><strong>Technical</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass (kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Satellite (wet)</td>
<td>211</td>
<td>612</td>
</tr>
<tr>
<td>Spacecraft (dry)</td>
<td>134</td>
<td>414</td>
</tr>
<tr>
<td>Payload</td>
<td>69</td>
<td>133</td>
</tr>
<tr>
<td>Power (W)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Satellite (Orbit Average)</td>
<td>152</td>
<td>515</td>
</tr>
<tr>
<td>Payload (Orbit Average)</td>
<td>58</td>
<td>108</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transponder Power (W)</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>Downlink Data Rate (kbps)</td>
<td>150</td>
<td>720</td>
</tr>
<tr>
<td>Data Storage (Gb)</td>
<td>1</td>
<td>8</td>
</tr>
</tbody>
</table>

Effect of Increased Complexity on Flight System Cost: STEREO Complexity Increased from 40% to 60%*

System Cost as Function of Complexity

\[ y = 11.523e^{0.7802x} \]

\[ R^2 = 0.8832 \]

Effect of Increased Complexity on Development Time: 
STEREO Complexity Increased from 40% to 60%*

\[ y = 24.22e^{1.6479x} \]

\[ R^2 = 0.6889 \]

Schedule as Function of Complexity

Typical Cost-risk Analyses Won’t Capture Large Changes During Concept Evolution*

*“An Assessment of the Inherent Optimism in Early Conceptual Designs and its Effect on Cost and Schedule Growth”, Freaner C., Bitten R., Bearden D., and Emmons D.
Inadequate Budget Planning for One Project Results in a Domino Effect for Other Projects in the Program Portfolio

Although the total program funding remained essentially the same over this time period, implementation of successive missions (e.g. MMS) was substantially affected.

Total Program Funding 1999-2006
• Planned = $689M
• Actual = $715M
Summary

• Methods exist to estimate cost and schedule at the conceptual phase albeit with some level of uncertainty

• The greatest growth manifests itself late in project during Integration & Test

• Data highlighted that the primary reason for cost and schedule growth is internal project technical and development issues often associated with instruments

• Initial project estimates may be unreliable due to design and technology immaturity and inherent optimism

• Success dependence on system complexity and adequacy of resources observed with identification of a “no-fly zone”

• Better technical and programmatic appraisal early in lifecycle is needed along with independent assessment of design and programmatic assumptions
References and Further Reading


