Estimating the Cost of Space Systems

JUST THE BASICS

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Introduction

- Iterative process
- Not an exact science
  - No absolute right answer to the question;
    “How much will it cost?”
- Typical cost drivers
  - Weight (H/W)
  - Lines of code (S/W)
  - Complexity
  - TRL
  - Schedule
- All estimates based on analogies
Cost Estimating Relationships (CERs)

- What is a CER?
  - A statistically-based, cost-predicting algorithm derived from historical data bases
    - Earlier designs
    - Similar configurations or missions
  - CERs relate the **Dependent** variables (dollars, labor, hours) to the **Independent** variables (weight, complexity, amount of code, time)
  - Aggregate of CERs $\rightarrow$ parametric cost model
Cost Estimating Methods

- Detailed bottoms-up cost estimating
  - Most accurate; but, most time consuming
  - Best applied late in program

- Analogous Estimating
  - Can be applied at any level of design

- Parametric estimation
  - Based on CERs
  - Best for trade studies during conceptual design
  - **Caveat #1**: CERs only applicable to the range of historical data utilized
  - **Caveat #2**: Not useful for projects involving major technological advancements or fundamental paradigm shifts
Cost Elements of the Space System

- Program Costs
  - Management
  - SE&I

- Spacecraft Segment
  - Option A
    - Systems Level
    - Payload (IA&T)
    - Spacecraft Bus (IA&T)
  - Option B
  - Option Z

- Launch Segment
  - Launch Vehicle
  - Launch Ops.

- Ground Segment
  - Facilities
  - Equipment
  - Software
  - Logistics
  - Management
  - SE&I

- Operations & Maintenance
  - Personnel Training
  - Maintenance
  - Spares
  - Mission Operations
  - Command, Communication, and Control

DDT&E = Design, Development, Test & Evaluation
O&M = Operations and Maintenance
SE&I = Systems Engineering and Integration
IA&T = Integration, Assembly, and Test
Types of Costs

- Non-recurring costs
  - Costs associated with qual test unit or prototype
    - Design, development, fabrication, test
    - Some level of ground support
  - Does not produce a flight unit
  - To turn qual unit into a flight unit, + 30%

- Recurring costs
  - Costs associated with **follow on** spacecraft
    - H/W and S/W
    - IA&T
    - Launch support
    - Flight ops
# Phases of Cost Estimating

## Development
- Breadboards, brass boards, prototypes, qual units
  - Design
  - Analysis
  - Test
- Non-recurring costs

## Production
- Theoretical first unit (TFU or T1)
- Production units
  - Manufacture of components
  - Assembly of flight units
  - Launch
- Recurring costs

## Operations
- Cost of flying
  - On-going ops
  - Maintenance
  - S/C replacement
  - S/W updates
  - End-of-life
- Recurring costs
Top-Down Cost Estimating Models

- Parametric cost estimation
  - Most common (and preferred) method used in early design phases
  - Models, CERs, and Factors (simplified CERs)
- Three categories of models
  - **Publicly available special purpose models**
    - Government agencies, research centers, universities
    - Typically available at no cost
    - USCM8, NICM, COCOMO81
  - Publicly available general purpose models
  - Private special purpose models
Examples Using Factors

<table>
<thead>
<tr>
<th>WBS Element</th>
<th>Develop Cost/kg 2010$K</th>
<th>TFU/kg 2010$K</th>
</tr>
</thead>
<tbody>
<tr>
<td>WBS 1.0 Earth Orbital SC (typical)</td>
<td>311</td>
<td>71</td>
</tr>
<tr>
<td>• WBS 1.0 - Communication SC</td>
<td>429</td>
<td>90</td>
</tr>
<tr>
<td>• WBS 1.0 – Mapping or Meteorological</td>
<td>277</td>
<td>52</td>
</tr>
<tr>
<td>• WBS 1.0 - Observatory</td>
<td>129</td>
<td>33</td>
</tr>
<tr>
<td>• WBS 1.0 – Positioning, Navigation</td>
<td>475</td>
<td>55</td>
</tr>
<tr>
<td>• WBS 1.0 - Science</td>
<td>238</td>
<td>83</td>
</tr>
</tbody>
</table>

For a small communications satellite (175kg), the predicted, non-recurring development Cost would be \(429 \times 175 = \$75\text{M}\). Recurring TFU Production costs should be \(90 \times 175 = \$16\text{M}\).

<table>
<thead>
<tr>
<th>WBS Element</th>
<th>Avg. SLOC per MM*</th>
<th>Typical Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>WBS 1.1.8 Flight S/W</td>
<td>111</td>
<td>SC control</td>
</tr>
<tr>
<td>WBS 3.0 Ground S/W</td>
<td>340</td>
<td>Ground ops</td>
</tr>
<tr>
<td>WBS 3.0 Instrument Ops</td>
<td>362</td>
<td>Sensor control</td>
</tr>
<tr>
<td>WBS 3.0 Image Process</td>
<td>161</td>
<td>Highly algorithmic</td>
</tr>
</tbody>
</table>

*Based on 152 hrs/MM

The predicted development of 10,000 SLOC of flight S/W should require \(10,000/111\) or 90 man-months of labor which converts to \(90 \times 152 = 13,694\) billable hours.
## Unmanned Space Vehicle Cost Model, Version 8 (USCM8)

Non-Recurring CERs in FY2010 $K

<table>
<thead>
<tr>
<th>WBS Element</th>
<th>Y=Non-recurring Cost of Development + One Qual Unit</th>
<th>Cost Drivers</th>
<th>Cost Driver Input Range</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 SC Bus</td>
<td>$Y = 110.2(X1)$</td>
<td>$X1=SC$ Weight (kg)</td>
<td>114-5,127 kg</td>
<td>47%</td>
</tr>
<tr>
<td>1.1.1/1.1.2 Structure &amp; Thermal Control</td>
<td>$Y = 646(X1)^{0.684}$</td>
<td>$X1=Structure + Thermal Weight (kg)$</td>
<td>59-501 kg</td>
<td>22%</td>
</tr>
<tr>
<td>1.1.3 ADCS</td>
<td>$Y = 342(X1)$</td>
<td>$X1=ADCS$ Weight (kg)</td>
<td>35-524 kg</td>
<td>44%</td>
</tr>
<tr>
<td>1.1.4 EPS</td>
<td>$Y = 64.3(X1)$</td>
<td>$X1=EPS$ Weight (kg)</td>
<td>47-1,065 kg</td>
<td>41%</td>
</tr>
<tr>
<td>1.1.5 Propulsion</td>
<td>$Y = 20.0(X1)^{0.485}$</td>
<td>$X1=Total$ RCS Tank Volume (cubic cm)</td>
<td>Not given</td>
<td>35%</td>
</tr>
<tr>
<td>1.1.6 TT&amp;C</td>
<td>$Y = 26,916$</td>
<td>$Y=Average$ TT&amp;C cost. No statistical CER for this element</td>
<td>CER based on S-Band telemetry</td>
<td>No given</td>
</tr>
<tr>
<td>WBS Element</td>
<td>CER</td>
<td>Cost Drivers</td>
<td>Cost Driver Input Range</td>
<td>SEE (Standard Error Estimate)</td>
</tr>
<tr>
<td>-------------------</td>
<td>-----</td>
<td>--------------------------------</td>
<td>---------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>1.0 Unmanned Robotic Mission</td>
<td></td>
<td></td>
<td></td>
<td>41%</td>
</tr>
<tr>
<td></td>
<td>Dry Mass</td>
<td>SC bus &amp; inst. (kg)</td>
<td>76 to 14,475 kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td>BOLP in watts</td>
<td>90 to 10,000 W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Data %</td>
<td>Data rate percentile</td>
<td>0 to 100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Life</td>
<td>Design life (months)</td>
<td>6 to 180 months</td>
<td></td>
</tr>
<tr>
<td></td>
<td>% New</td>
<td>Percent new fraction</td>
<td>28% to 130%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Planetary No=0, Yes=1</td>
<td>0 for earth orbit 1 for planetary</td>
<td>0 or 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Year</td>
<td>ATP date in four digits</td>
<td>1961 to 2005</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Instrument Complexity%</td>
<td>Instrument complexity relative to average</td>
<td>0% to 100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Team</td>
<td>Team experience (1-4)</td>
<td>1 to 4</td>
<td></td>
</tr>
</tbody>
</table>
QuickCost Regression Model

\[ Y = \text{total cost of development plus one protoflight unit in 2010 dollars} \]

\[ Y = 2.829 \times (\text{Dry Mass}^{0.457}) \times (\text{Power}^{0.157}) \times (2.718^{(0.171 \times \text{Data} \%)}) \times (2.718^{(0.00209 \times \text{Life})}) \times \]
\[ (2.718^{(1.52 \times \text{New})}) \times (2.718^{(0.258 \times \text{Planetary})}) \times 1/(2.718^{(0.0145 \times (\text{Year}-1960)}) \times \]
\[ (2.718^{(0.467 \times \text{InstrComp} \%)}) \times 1/(2.718^{(0.237 \times \text{Team})}) \]

1. Cost in millions of 2010 dollars including Phase B – Phase C/D
2. Includes all contractor cost through fee
3. Includes NASA full cost support
4. Includes spacecraft bus and instruments DDT&E plus TFU
5. Does not include launch services
6. Add 2% for Phase A
7. Add 9% for Ground Station
8. Add 5% per year for Mission Ops and Data Analysis
Estimating Software Costs Using COCOMO81

- Originally, software costs were estimated as a percentage of hardware costs
- COCOMO81 is time tested and maintained by USC Center for Systems and Software Engineering
- Basic equation: Effort (MM) = 3.312(KSLOC)^{1.2} \times \pi EAF
  - EAF = \textit{effort adjustment factor}
- Number of source lines of code (SLOC) must be estimated
- \pi EAF = \text{cumulative product of EAFs}
- (EAF_1 \times EAF_2 \times EAF_3 \times \ldots \times EAF_n) \quad \text{Total of 15 EAFs}
- To develop 10,000 new SLOC --- \textbf{Effort (MM) = 3.312(10)^{1.2} \times 1.0 = 52.5 MM}
  - If cost per MM = $25,000, cost = $1,312K or \approx $131 per SLOC
  - Assumes a nominal cumulative EAF (unrealistic)
Software Development Schedule

- The number of Man Months to develop 10,000 SLOC
  - 52.5 MM
- COCOMO8 equation to calculate the development duration
  - Duration (in months) = $4.376 \times (MM)^{0.32}$
    - Duration in calendar months to complete S/W development
    - Requirements analysis, coding, assembly, testing, documentation
    - MM = effort in man months derived from equation on previous slide
  - Using 52.5 MM  Duration = $4.376 \times (52.5)^{0.32} = 15.5$ months
  - Staff loading = 52.5MM/15.5 months = 3.4 persons
  - Cost = 15.5 months x $25,000 $/MM x 3.4 = $1,317K
### Software Development Cost Drivers (EAFs)

<table>
<thead>
<tr>
<th>Rating</th>
<th>Cost Driver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Low</td>
<td>Required reliability</td>
</tr>
<tr>
<td>Low</td>
<td>Database size</td>
</tr>
<tr>
<td>Nominal</td>
<td>Product complexity</td>
</tr>
<tr>
<td>High</td>
<td>Execution time constraint</td>
</tr>
<tr>
<td>Very High</td>
<td>Main storage constraint</td>
</tr>
<tr>
<td>Extra High</td>
<td>Virtual machine volatility</td>
</tr>
<tr>
<td></td>
<td>Computer turnaround time</td>
</tr>
<tr>
<td></td>
<td>Analyst capability</td>
</tr>
<tr>
<td></td>
<td>Applications experience</td>
</tr>
<tr>
<td></td>
<td>Programmer capability</td>
</tr>
<tr>
<td></td>
<td>Virtual machine experience</td>
</tr>
<tr>
<td></td>
<td>Programming language experience</td>
</tr>
<tr>
<td></td>
<td>Modern programming practices</td>
</tr>
<tr>
<td></td>
<td>Use of software tools</td>
</tr>
<tr>
<td></td>
<td>Required development schedule</td>
</tr>
</tbody>
</table>

**COCOMO Calculator:**
[http://sunset.usc.edu/research/COCOMOII/cocomo81_pgm/cocomo81.html](http://sunset.usc.edu/research/COCOMOII/cocomo81_pgm/cocomo81.html)
Estimating Launch Costs

- Use existing cost history
- Select one or more LVs
  - Required orbit, payload capability, trajectory,
  - Availability

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Country</th>
<th>Kg to LEO</th>
<th>Kg to GTO</th>
<th>$ per kg</th>
<th>$ per kg LEO</th>
<th>$ per kg GTO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Small</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Falcon 1e</td>
<td>USA</td>
<td>1,010</td>
<td>N/A</td>
<td>$10,900K</td>
<td>$10.8K</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Medium to Intermediate</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atlas 2AS</td>
<td>USA</td>
<td>8,618</td>
<td>3,719</td>
<td>$132,795K</td>
<td>$15.4K</td>
<td>$35.7K</td>
</tr>
<tr>
<td><strong>Heavy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delta 4 Hvy</td>
<td>USA</td>
<td>22,560</td>
<td>13,130</td>
<td>$215,000K</td>
<td>$9.5K</td>
<td>$16.4K</td>
</tr>
</tbody>
</table>
Additional Costs

- Wrap costs – added to the “prime mission equipment (PME) costs
  - 3.0 Ground station support
  - 4.0 Program level
    - System Engineering
    - Project Management
    - Configuration Management
    - Etc. (SME The New SMAD, Table 11-24)
  - 7.0 Operations
Performance/Cost Trade Space

- **Performance Threshold**: Marginally acceptable performance
- **Best Bang for the Buck**: Probably customer's budget
- **Expenditure, $**: Maximum allowable cost

Legend:
- **1**: Threshold of acceptable performance
- **2**: Marginal performance improvements
- **3**: Probably customer's budget
- **4**: Maximum allowable cost
You Will Estimate the Cost of LUNA

- QuickCost Regression Model for development costs
  - Prime mission equipment (PME)
- COCOMO8 for software costs
- Launch vehicle costs
- Wrap factors: SME The New SMAD, Table 11-24
  - Percentage of development cost
  - Only need to include those factors that apply
  - Examine resulting number for “sanity”, i.e.; Does it make sense?
## Wrap Factors

<table>
<thead>
<tr>
<th>SME-SMAD WBS Element</th>
<th>Minimum Factor</th>
<th>Average Factor</th>
<th>Maximum Factor</th>
<th>Reasons for Using the Maximum Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0 Annual Operations and Support for Ground Station</td>
<td>1%</td>
<td>5%</td>
<td>27%</td>
<td>Many subsystems and platforms, contractor support</td>
</tr>
<tr>
<td>4.1 System Engineering</td>
<td>15%</td>
<td>20%</td>
<td>35%</td>
<td>Frequently changing requirements, multiple interfaces</td>
</tr>
<tr>
<td>4.2 Project Management</td>
<td>10%</td>
<td>15%</td>
<td>35%</td>
<td>Small project; multiple team members or working locations</td>
</tr>
<tr>
<td>4.3 System Integration &amp; Test</td>
<td>1%</td>
<td>15%</td>
<td>33%</td>
<td>Many components, conflicting requirements, changing baseline</td>
</tr>
<tr>
<td>4.4 Product Assurance</td>
<td>1%</td>
<td>3%</td>
<td>6%</td>
<td>Anticipated short life, harsh operating environment</td>
</tr>
<tr>
<td>4.5 Configuration Management</td>
<td>1%</td>
<td>4%</td>
<td>20%</td>
<td>Detailed control level, multiple users</td>
</tr>
<tr>
<td>4.5 Contractor (or subcontractor) Fee</td>
<td>10%</td>
<td>12%</td>
<td>15%</td>
<td>Contractor assumes project risk, such as with fixed price contract</td>
</tr>
<tr>
<td>4.5 Data Management</td>
<td>1%</td>
<td>2%</td>
<td>5%</td>
<td>Multiple data clients, multiple IT platforms</td>
</tr>
<tr>
<td>4.5 Development Support Facility</td>
<td>1%</td>
<td>4%</td>
<td>11%</td>
<td>Real time support, multiple operating locations</td>
</tr>
<tr>
<td>4.5 Hardware/Software Integration</td>
<td>10%</td>
<td>16%</td>
<td>24%</td>
<td>When hardware or software components are still being developed</td>
</tr>
<tr>
<td>4.5 Integrated Logistics</td>
<td>1%</td>
<td>6%</td>
<td>15%</td>
<td>Multiple operating platforms, multiple operating agencies</td>
</tr>
<tr>
<td>4.5 Safety &amp; Mission Assurance (S&amp;MA)</td>
<td>7%</td>
<td>7%</td>
<td>8%</td>
<td>When human life is at risk</td>
</tr>
<tr>
<td>4.5 Site Activation</td>
<td>1%</td>
<td>3%</td>
<td>6%</td>
<td>Remote area, crowded environment, harsh climate</td>
</tr>
</tbody>
</table>