Leveraging Performance-Based Cost Modeling

Elizabeth A. Koltz, USC
Anthony Shao, USC/Microcosm
James R. Wertz, USC/Microcosm

Contact: Elizabeth Koltz
chapmane@usc.edu
Phone: 310-219-2700
http://www.smad.com/ReinventingSpace.html

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- Reinventing Space Project Summary
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- Results for Earth Observing System
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  - Cost vs. Altitude for Fixed Coverage and Resolution
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  - Risk, Reliability, and Schedule
  - Cost vs. Cost Overruns
  - Reinventing Space Project Overview
Executive Summary

- Sequestration 2013 made clear that government spending has to be reduced

- How to reduce mission space costs is well defined, but contrary to current M.O.
  - For Earth Observing Missions, lower the altitude
  - Reduce physical size of spacecraft
  - Launch more satellites, and more frequently (economies of scale and lower risk)
  - Lower parts reliability, increase mission reliability
  - Larger margin
  - Use microprocessors and modern electronics
  - Reduce development schedule
  - Trade on requirements

- We are presenting to the cost community today to determine:
  1. Whether Performance Based Cost Modeling (PBCM) is an appropriate method to quantify cost savings.
  2. How do we convince the elephants to change how we do business in space?
• We believe the 3 highest priority problems in space systems are:
  1. They cost too much
  2. They take too long
  3. They are not as responsive or robust as they should be

• What do we want to achieve?
  – Reduce space mission cost — by a factor of 2 to 10
  – Reduce the schedule for new programs — from decades to months or years
  – Reduce the cost of access to space — by a factor of 2 to 5 initially, 4 to 10 in the longer term
  – Provide responsive launch (within 8–24 hours) to respond to natural or man-made disasters
  – Provide frequent, low-cost access to space for education, innovation, and testing
  – Create evidence that these goals are attainable
Preliminary Results & Future Goals

**Initial Results:**
- Earth Observation Systems

**Future Goals:**
- Communication Satellite Systems
- Interplanetary Missions

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**Cost vs. Altitude for Fixed Resolution and Coverage**
- Mission Cost for 8 yrs (FY13SM)
- Graph depicting cost vs. altitude with data points for GeoEye-2, QuickBird, NanoEye, and Solar Mean.

**Number of satellites required for coverage**
- Graph showing number of satellites required for coverage at different altitudes with lines for Circular, SOC, and Elliptical coverage and redundancy, and mission life.

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**Notes:**
- Altitude [km]
- T, number of satellites required for coverage
- Geometric consideration for satellite placement and coverage.
Objectives for Performance-Based Cost Modeling (PBCM)

- **Objective: Quantify the relationship between Cost and Performance**
  - **Cost:** dollar amount spent on entire program
    - Includes costs for Non-recurring engineering, recurring, launch, operations & maintenance, production with learning curves, and amortization of costs
  - **Performance:** first priority technical program objective
    - For Earth Observation: Resolution and Coverage Rate
    - For Communication Systems: Data Rate and Coverage Rate
- Illuminate useful mission design alternatives
  - Lower cost, better performance, or both
- SmallSats are inherently lower cost than large satellites
  - PBCM aims to quantifiy cost saving methods

Today, most acquisition performance analysis focuses on cost overruns i.e., how much does the system cost relative to what we expected it to cost?

PBCM allows us to focus on the more important questions of how much performance we can achieve for a given cost, or what the cost is for a given level of performance.
PBCM Process

• Determine the performance requirements
  – Sensing requirement: Visible EO Imaging for baseline mission
  – Resolution at nadir: 0.5 m for baseline mission
  – Coverage: 14,200 km²/sec for baseline mission
  – Mission lifetime: 8 years for baseline mission

• Estimate total mission cost from performance parameters
  1. Size the payload required to meet the desired resolution
  2. Size the spacecraft bus to support the payload
  3. Size the spacecraft wet mass (in appendix)
  4. Determine number of satellites required for coverage and lifetime requirements
  5. Input mass estimates into weight-based cost model CERs to predict WBS costs
  6. Determine launch cost (in appendix)
  7. Determine recurring and non-recurring engineering costs (in appendix)
  8. Estimate total mission costs

• Present the relationship between total mission cost and performance
  9. Total Mission Cost vs. Orbit Altitude for fixed Resolution and Coverage
1. Sizing the Payload & 2. Sizing the Spacecraft Bus

- Determine the payload aperture diameter using diffraction limited optics for Earth Observation mission
  - \( D = \) Aperture diameter
  - \( \theta = \) Resolution requirement
  - \( h = \) Orbital altitude
  - \( \lambda = \) Observation wavelength
  \[
  D = \frac{h \, \lambda}{\theta}
  \]

- Spacecraft bus density is estimated empirically from 6 existing observation systems:
  - GeoEye-1
  - GeoEye-2
  - Quickbird
  - OrbView-3
  - Kestrel Eye
  - NanoEye
  \[
  M_{dry} = 2287D^3
  \]

- Less redundancy needed for systems with shorter design-life
  - Spacecraft with longer design-life typically include parts redundancy in case of failures
  - For single-string systems, we assume reduced bus mass by 30%
4. Number of Satellites Required

- Determine the initial number of satellites required in orbit
  - Based on the coverage requirement
  - Assuming circular orbits (future models will study elliptical orbits)
  - Coverage is a function of orbit altitude and minimum working elevation angle
  - At lower altitudes the coverage rate decreases, thus increasing the number of satellites required at lower altitudes

- Determine how many more satellites are required for the mission life
  - Based on the lifetime requirement
  - Assume satellite design life is proportional to the orbit altitude
    - e.g., 8 years at 800 km, 4 years at 400 km, 2 years at 200 km
    - Sizing the wet mass of the spacecraft takes this assumption into account
  - We can simply estimate number of replacement satellites needed

- Assume 10% launch failure
  - Increases the number of spacecraft needed to account for launch failures
5. Traditional Space System Cost Models

- Traditional space system cost models can effectively predict space system cost trends
  - Empirically weight-based (adjustments for power/data rate)
  - Mass budgets available early in mission design
  - Mass historically correlates well with actual hardware costs
  - Although not a substitute for detailed engineering design

- Cost models leveraged in this PBCM analysis:
  - **Unmanned Space Vehicle Cost Model (USCM), Version 8** – Tecolote Research/USAF SMC
  - **NASA Instrument Cost Model (NICM), Version IIIC** – NASA Jet Propulsion Laboratory
  - **Small Satellite Cost Model (SSCM), 1996** – The Aerospace Corporation

- This ensures that the results will be consistent with widely accepted cost models

**Are USCM, NICM, and SSCM valid and sufficient? Should we use more/different models?**

Table 11-11. SSCM Earth Orbiting Total Non-recurring Cost (development plus one protoflight unit) CERs in FY2010 Thousands of Dollars. Useful for spacecraft weighing less than 500 kg. It is presumed that these CERs include the cost of contractor program management, systems engineering, product assurance, and I&T. See Tables 11-35 and 11-38 for application of these CERs.

<table>
<thead>
<tr>
<th>SME-SMAD WBS Element</th>
<th>CER</th>
<th>Cost Driver(s)</th>
<th>Cost Driver Input Range</th>
<th>Standard Error of Estimate (absolute) FY10 $</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1.1 Spacecraft</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1 Spacecraft Bus (alternate CER when no component information is available)</td>
<td>Y = 1,064 + 35.5 X^{1.261}</td>
<td>X = Spacecraft Bus Dry Weight (kg)</td>
<td>20–400 kg</td>
<td>3,696</td>
</tr>
<tr>
<td>1.1.1 Structure</td>
<td>Y = 407 + 19.3 X \ln(X)</td>
<td>X = Structure Weight (kg)</td>
<td>5–100 kg</td>
<td>1,097</td>
</tr>
<tr>
<td>1.1.2 Thermal Control</td>
<td>Y = 335 + 5.7 X^2</td>
<td>X = Thermal Control Weight (kg)</td>
<td>5–12 kg</td>
<td>119</td>
</tr>
<tr>
<td>1.1.3 Attitude Determination &amp; Control System (ADCS)</td>
<td>Y = 1,850 + 11.7 X^2</td>
<td>X = ADCS Dry Weight (kg)</td>
<td>1–25 kg</td>
<td>1,113</td>
</tr>
<tr>
<td>1.1.4 Electrical Power Supply (EPS)</td>
<td>Y = 1,261 + 539 X^{0.72}</td>
<td>X = EPS Weight (kg)</td>
<td>7–70 kg</td>
<td>910</td>
</tr>
<tr>
<td>1.1.5 Propulsion (Reaction Control)</td>
<td>Y = 89 + 3.0 X^{1.261}</td>
<td>X = Spacecraft Bus Dry Weight (kg)</td>
<td>20–400 kg</td>
<td>310</td>
</tr>
<tr>
<td>1.1.6a Telemetry, Tracking, &amp; Command (TT&amp;C)</td>
<td>Y = 486 + 55.5 X^{1.35}</td>
<td>X = TT&amp;C Weight (kg)</td>
<td>3–30 kg</td>
<td>629</td>
</tr>
<tr>
<td>1.1.6b Command &amp; Data Handling (CD&amp;H)</td>
<td>Y = 658 + 75 X^{1.35}</td>
<td>X = Command &amp; Data Handling Weight (kg)</td>
<td>3–30 kg</td>
<td>854</td>
</tr>
<tr>
<td><strong>1.2 Payload</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2 Payload</td>
<td>Y = 0.4 X</td>
<td>X = Spacecraft Bus Total Cost ($K)</td>
<td>2,600–69,000 ($K)</td>
<td></td>
</tr>
<tr>
<td><strong>1.3 Spacecraft Integration, Assembly, and Test</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3 Integration, Assembly, &amp; Test (I&amp;A&amp;T)</td>
<td>Y = 0.139 X</td>
<td>X = Spacecraft Bus Total Cost ($K)</td>
<td>2,600–69,000 ($K)</td>
<td></td>
</tr>
<tr>
<td><strong>4.0 Program Level</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.0 Program Level</td>
<td>Y = 0.229 X</td>
<td>X = Spacecraft Bus Total Cost ($K)</td>
<td>2,600–69,000 ($K)</td>
<td></td>
</tr>
<tr>
<td><strong>5.0 Flight Support</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.0 Launch &amp; Orbital Operations Support (LOOS)</td>
<td>Y = 0.061 X</td>
<td>X = Spacecraft Bus Total Cost ($K)</td>
<td>2,600–69,000 ($K)</td>
<td></td>
</tr>
<tr>
<td><strong>6.0 Aerospace Ground Equipment</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.0 Ground Support Equipment (GSE)</td>
<td>Y = 0.066 X</td>
<td>X = Spacecraft Bus Total Cost ($K)</td>
<td>2,600–69,000 ($K)</td>
<td></td>
</tr>
</tbody>
</table>

[Wertz, Everett, and Puschell, 2011]
8. Total Mission Cost

• Upfront cost for Theoretical First Unit (TFU) is the sum of:
  – Non-recurring engineering cost
  – Recurring engineering cost

• Standard Wright learning curve applied to multiple units after the TFU
  – Conservative 90% learning curve assumed
  – NASA Cost Estimating Handbook recommends 85% learning curve for aerospace industry

• Production of multiple units has the advantage of postponing costs
  – It is more expensive to spend money now than it is to spend money down the road when you account for the Time Value of Money
  – Amortize cost over the mission lifetime (spread payments out over time)
  – Higher altitude missions with less satellites have to be paid for up front
  – Lower altitude missions with shorter design-life and more satellites to build have more opportunities to postpone payments

• The total mission cost takes all the factors above into account and generates a final estimate of the total mission cost
Baseline Requirements and Input Assumptions for Earth Observing Systems

## Assumptions

<table>
<thead>
<tr>
<th>Assumptions</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution (m)</td>
<td>0.5</td>
</tr>
<tr>
<td>Area Access Rate (AAR) at 800 km Altitude (km²/s)</td>
<td>14,217</td>
</tr>
<tr>
<td>Mission Life Requirement (yrs)</td>
<td>8</td>
</tr>
<tr>
<td>Wavelength to Observe (nm)</td>
<td>550</td>
</tr>
<tr>
<td>Spacecraft/Payload Average Density (kg/m³)</td>
<td>79</td>
</tr>
<tr>
<td>Propellant Density (kg/m³)</td>
<td>1000</td>
</tr>
<tr>
<td>Dry Mass/ Aperture³</td>
<td>2287</td>
</tr>
<tr>
<td>Payload % of Total S/C Dry Mass</td>
<td>31%</td>
</tr>
<tr>
<td>Spacecraft Power/Spacecraft Dry Mass (W/kg)</td>
<td>1.3</td>
</tr>
<tr>
<td>Payload Power Percentage of Spacecraft Power (W)</td>
<td>46%</td>
</tr>
<tr>
<td>Spacecraft Datarate at 800 km Altitude (kbps)</td>
<td>800,000</td>
</tr>
<tr>
<td>Drag Coefficient</td>
<td>2</td>
</tr>
<tr>
<td>Solar State (Min, Mean, Max)</td>
<td>Mean</td>
</tr>
<tr>
<td>Minimum Working Elevation Angle (deg)</td>
<td>30</td>
</tr>
<tr>
<td>Percentage of Launches that Fail</td>
<td>10%</td>
</tr>
<tr>
<td>Min. No. Sats for No System Redundancy</td>
<td>2</td>
</tr>
<tr>
<td>Spacecraft Propellant Isp</td>
<td>235</td>
</tr>
<tr>
<td>Learning Curve</td>
<td>90%</td>
</tr>
<tr>
<td>Amortization Rate</td>
<td>8%</td>
</tr>
<tr>
<td>Cumulative Savings Effect of Amortization</td>
<td>19%</td>
</tr>
</tbody>
</table>

Input Assumptions intended to represent a realistic mission.
9. PBCM Results – Physical Parameters

<table>
<thead>
<tr>
<th>Physical Parameters</th>
<th>Model Predictions</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NanoEye</td>
<td>Quickbird</td>
</tr>
<tr>
<td>Orbital Altitude (km)</td>
<td>200</td>
<td>400</td>
</tr>
<tr>
<td>Resolution (m)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Payload Aperture Diameter (m)</td>
<td>0.22</td>
<td>0.44</td>
</tr>
<tr>
<td>Spacecraft Dry Mass (kg)</td>
<td>24.4</td>
<td>194.8</td>
</tr>
<tr>
<td>Non-Redundancy Mass Reduction</td>
<td>30.0%</td>
<td>20.0%</td>
</tr>
<tr>
<td>Corrected Spacecraft Dry Mass (kg)</td>
<td>17.0</td>
<td>155.9</td>
</tr>
<tr>
<td>Spacecraft Wet Mass (kg)</td>
<td>292.5</td>
<td>181.1</td>
</tr>
<tr>
<td>Payload Power (W)</td>
<td>10.2</td>
<td>93.5</td>
</tr>
<tr>
<td>Spacecraft Area Access Rate (km²/sec)</td>
<td>4,858</td>
<td>8,696</td>
</tr>
<tr>
<td>Satellite Orbital Period (min)</td>
<td>88.5</td>
<td>92.6</td>
</tr>
<tr>
<td>Spacecraft Design Lifetime (yrs)</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>No. of Sats Needed for Same Coverage at Any Given Time</td>
<td>2.9</td>
<td>1.6</td>
</tr>
<tr>
<td>Number of Satellites Required for Entire Mission</td>
<td>11.7</td>
<td>3.3</td>
</tr>
<tr>
<td>Number of Redundant Satellites</td>
<td>1.2</td>
<td>0.3</td>
</tr>
<tr>
<td>No. of Satellites to Build w/ System Redundancy*</td>
<td>12.9</td>
<td>3.6</td>
</tr>
<tr>
<td>Total Launch Mass (kg)</td>
<td>3,767</td>
<td>651</td>
</tr>
</tbody>
</table>

* Note that fractions of satellites have been allowed in this model for purposes of comparison simplicity and a smoother display of results.

To satisfy the baseline mission, we compare three options:

A. 1.0 (1,559-kg) traditional large satellite flown at 800 km
B. 3.6 (156-kg) satellites flown at 400 km
C. 12.9 (17-kg) SmallSats flown at 200 km

For a fixed resolution, reducing the altitude by a factor of 4 reduces the individual spacecraft bus mass by almost 2 orders of magnitude.
9. PBCM Results – Cost Predictions
Using USCM8 and SSCM Cost Models

The tables have different results because USCM8 is developed by parametric cost modeling of traditional large satellites, and similarly, parametric cost modeling of small satellites for SSCM.
9. Key PBCM Results
Total Mission Cost vs. Altitude

Cost vs. Altitude for Fixed Resolution and Coverage

For the same resolution and coverage, we can potentially dramatically reduce mission cost by using multiple smaller satellites at a lower altitude.
Variation in Inputs for Earth Observing Systems

Changing the learning curve input has very little impact on the relative results. Other variations in inputs assumptions shift the curves up or down insignificantly as well.

Varying the input assumptions does not change the relative results of the study.
Conclusions for SmallSat Earth Observing Systems

• Past Earth observation systems have used traditional space technology to achieve the best possible performance, but have been very expensive
  – In addition, low-cost, responsive dedicated launch has not been available for SmallSats
• Using modern microelectronics, future SmallSat observation systems at a lower altitude than traditional systems have the potential for:
  – Much Lower Overall Mission Cost
  – Comparable or Better Performance (Resolution and Coverage)
  – Lower Risk (both Implementation and Operations)
  – Shorter Schedule
• Relevant secondary advantages for the low-altitude SmallSats include:
  – Lower up-front development cost  – More responsive to both new technology and changing needs
  – More sustainable business model  – Mitigates the problem of orbital debris
  – More flexible and resilient
• The principal disadvantages of the SmallSat observation system are:
  – Needs greater FoV agility than larger, higher altitude systems
    • Needed agility is inversely proportional to altitude, but moments of inertia are also much less
  – Needs responsive, low-cost, small launch system for operational missions
  – Requires changing the way we do business in space and how we think about using space systems (the biggest challenge)

For Earth observing, a major increase in performance, reduction in cost, or both is possible by using multiple SmallSats at significantly lower altitudes for future missions.
Questions for the Cost Community

- Is this technique valid from a cost modeling perspective? Are our assumptions valid? Is there anything wrong with this method?

- Are USCM, NICM, and SSCM valid? Should we use more/different models?

- Would this technique provide adequate justification to influence design decisions?

- Are there similar techniques being used? What have their conclusions been?

- What can we do better?

What must be done to convince the elephants?
3. Sizing the Spacecraft Wet Mass

- The wet mass, \( M_{\text{wet}} = M_{\text{prop}} + M_{\text{dry}} \) is calculated iteratively using the following formulas:

\[
M_{\text{launch}} = M_{\text{dry}} + M_{\text{prop}}
\]

\[
M_{\text{prop}} = M_{\text{dry}} \left[ 1 - \exp \left( \frac{-\Delta V}{I_{sp} g_o} \right) \right]
\]

\[
\beta = \frac{C_D A}{M}
\]

\[
\Delta V = \frac{\pi \rho r v}{\beta T}
\]

- \( I_{sp} \): specific impulse of the propellant (A liquid monopropellant)
- \( g_o \): gravitational acceleration at the Earth’s surface
- \( \beta \): ballistic coefficient
- \( C_D \): satellite drag coefficient, assumed to be the same for every spacecraft in this model
- \( A \): satellite cross-sectional area along the velocity vector, assuming a spherical spacecraft
- \( M \): mass of the satellite (average of the satellite launch and dry masses)
- \( \Delta V \): total delta V required to maintain the mission altitude for the design life of the satellite
- \( \rho \): local atmospheric density
- \( r \): distance of the satellite from the central body (Earth)
- \( v \): orbital velocity of the satellite
- \( T \): orbital period of the satellite
5. Estimating Non-Recurring Costs with USCM8

Table 11-8. USCM8 Non-recurring Subsystem CERs in FY2010 Thousands of Dollars. These CERs predict the cost of development plus one qualification unit. See Tables 11-34 and 11-37 for application of these CERs.

<table>
<thead>
<tr>
<th>SME-SMAD WBS Element (Non-recurring subsystem)</th>
<th>Y = non-recurring cost in FY2010 thousands of dollars for development plus one qualification unit.</th>
<th>Cost Driver(s)</th>
<th>Cost Driver Input Range</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 Spacecraft Bus (alternate CER when no component information is available)</td>
<td>$Y = 110.2 \times X_1$</td>
<td>$X_1 = \text{Spacecraft Weight (kg)}$</td>
<td>114–5,127 kg</td>
<td>47%</td>
</tr>
<tr>
<td>1.1.1/1.1.2 Structure and Thermal Control</td>
<td>$Y = 646 \times 10^{0.084}$</td>
<td>$X_1 = \text{Structure + Thermal Weight (kg)}$</td>
<td>59–501 kg</td>
<td>22%</td>
</tr>
<tr>
<td>1.1.3 Attitude Determination &amp; Control System (ADCS)</td>
<td>$Y = 324 X_1$</td>
<td>$X_1 = \text{ADCS Weight (kg)}$</td>
<td>35–524 kg</td>
<td>44%</td>
</tr>
<tr>
<td>1.1.4 Electrical Power System (EPS)</td>
<td>$Y = 84.3 X_1$</td>
<td>$X_1 = \text{EPS Weight (kg)}$</td>
<td>47–1,085 kg</td>
<td>41%</td>
</tr>
<tr>
<td>1.1.5 Propulsion (Reaction Control)</td>
<td>$Y = 20.0 \times 10^{4.485}$</td>
<td>$X_1 = \text{Total RCS tank volume (cubic centimeters)}$</td>
<td>Not given</td>
<td>35%</td>
</tr>
<tr>
<td>1.1.6 Telemetry, Tracking, &amp; Command (TT&amp;C)</td>
<td>$Y = 26,916$</td>
<td>$Y = \text{Average TT&amp;C Cost (since there is no statistical CER for this element)}$</td>
<td>CER based on S-Band telemetry</td>
<td>Not given</td>
</tr>
</tbody>
</table>

1.2 Payload

| 1.2 Communications Payload (based on weight and number of channels) | $Y = 3.39 X_1 + 5,127 X_2$ | $X_1 = \text{Communications Subsystem Weight (kg)}$, $X_2 = \text{Number of Communication Channels}$ | 160–395 kg, 2–32 channels | 40% |
| 1.2 Communications Payload (alternate CER based on weight alone) | $Y = 618 X_1$ | $X_1 = \text{Communications Subsystem Weight (kg)}$ | 160–395 kg | 38% |

1.3 Spacecraft Integration, Assembly, and Test

| 1.3 Integration, Assembly, & Test (of bus and payload into spacecraft) | $Y = 0.195 X_1$ | $X_1 = \text{Spacecraft Bus + Payload Non-recurring Cost (SK)}$ | 3,600–545,000 $K$ | 42% |

4.0 Program Level

| 4.0 Program Level (for a Communications Satellite) | $Y = 0.239 X_1$ | $X_1 = \text{Space Vehicle and I&T Non-recurring Cost (SK)}$ | 7,850–353,804 $K$ | 23% |
| 4.0 Program Level (for an other than Communications Satellite) | $Y = 0.414 X_1$ | $X_1 = \text{Space Vehicle and I&T Non-recurring Cost (SK)}$ | 7,850–353,804 $K$ | 40% |

6.0 Aerospace Ground Equipment (AGE)

| 6.0 Aerospace Ground Equipment (AGE) | $Y = 0.421 X_1^{-0.967} \times 2.244^{X_2}$ | $X_1 = \text{Spacecraft Bus Non-recurring Cost (SK)}$, $X_2 = 0$ for comm sat and $X_2 = 1$ for non-comm sat | 7,650–353,804 $K$ | 37% |

[Wertz, Everett, and Puschell, 2011]
5. Estimating Recurring Costs with USCM8

The Payload CER is omitted for Earth Observation System and replaced with CERs found in NICM

<table>
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<tr>
<th>SME-SMAD WBS Element</th>
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<th>SEE</th>
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</tr>
<tr>
<td>1.1.3 Attitude Determination &amp; Control System (ADCS)</td>
<td>27-524 kg</td>
<td>35%</td>
</tr>
<tr>
<td>1.1.4 Electrical Power Supply (EPS)</td>
<td>111-1,479 kg</td>
<td>31%</td>
</tr>
<tr>
<td>1.1.5 Propulsion Apogee Kick Motor (AKM)</td>
<td>81-956 kg</td>
<td>22%</td>
</tr>
<tr>
<td>1.1.6 Telemetry, Tracking, &amp; Command (TT&amp;C)</td>
<td>12-76 kg for S-band</td>
<td>13%</td>
</tr>
<tr>
<td><strong>1.2 Payload</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2 Communications Payload</td>
<td>30-628 kg</td>
<td>39%</td>
</tr>
<tr>
<td>1.3 Integration, Assembly, &amp; Test (I&amp;A&amp;T) of bus and payload into space vehicle</td>
<td>35,367-142,044 SK</td>
<td>34%</td>
</tr>
<tr>
<td><strong>4.0 Program Level</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.0 Program Level (for a Communication Satellite)</td>
<td>13,287-268,225 SK</td>
<td>13%</td>
</tr>
<tr>
<td>4. Program Level (for an other than communication satellite)</td>
<td>13,287-268,225 SK</td>
<td>29%</td>
</tr>
<tr>
<td><strong>5.0 Flight Support</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.0 Launch Operations &amp; Orbital Support (LOOS)</td>
<td>Not given</td>
<td>Not given</td>
</tr>
</tbody>
</table>

(a) Current version of USCM8 provides a combined structure/thermal CER.

[Wertz, Everett, and Puschell, 2011]
5. Estimating Payload Costs with NICM

The Optical Earth-Orbiting Payload Element was used for this study, and replaces the payload CERs found in USCM8.

[Wertz, Everett, and Puschell, 2011]
6. Launch Costs

- Assumes single satellite launches
- Assumes 10% learning curve and amortizing cost
- Derived empirically using cost data from existing launch vehicles

\[ \text{Cost}_{\text{launch}} = 26.489 - 0.0015M_{\text{launch}} \]

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Capacity to LEO (kg)</th>
<th>Launch to LEO Cost/kg (FY13$K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pegasus XL</td>
<td>443</td>
<td>$43.64</td>
</tr>
<tr>
<td>Taurus</td>
<td>1,380</td>
<td>$19.77</td>
</tr>
<tr>
<td>Minotaur IV</td>
<td>1,650</td>
<td>$13.99</td>
</tr>
<tr>
<td>Athena</td>
<td>2,065</td>
<td>$16.61</td>
</tr>
<tr>
<td>Atlas 2AS</td>
<td>8,618</td>
<td>$16.19</td>
</tr>
<tr>
<td>Ariane 44L</td>
<td>10,200</td>
<td>$15.77</td>
</tr>
<tr>
<td>Falcon 9</td>
<td>10,450</td>
<td>$5.68</td>
</tr>
</tbody>
</table>

[Wertz, Everett, and Puschell, 2011]
### 7. Sample Breakdown of Upfront Cost

<table>
<thead>
<tr>
<th>Cost Estimates (FY$13M) - USCM8 (from Manual) and NICM (from SME)</th>
<th>Model Predictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Orbital Altitude (km)</td>
<td>200</td>
</tr>
<tr>
<td>2 Spacecraft Bus (Fabrication) Cost</td>
<td>$3.1</td>
</tr>
<tr>
<td>3 Spacecraft Bus NRE Cost</td>
<td>$1.34</td>
</tr>
<tr>
<td>4 Spacecraft Bus RE Cost</td>
<td>$1.7</td>
</tr>
<tr>
<td>5 Fraction of Spacecraft Bus RE/(RE+NRE)</td>
<td>57%</td>
</tr>
<tr>
<td>6 Payload (Fabrication) Cost</td>
<td>$15.3</td>
</tr>
<tr>
<td>7 Payload NRE Cost</td>
<td>$6.6</td>
</tr>
<tr>
<td>8 Payload RE Cost</td>
<td>$8.7</td>
</tr>
<tr>
<td>9 Payload Wrap Factor Costs</td>
<td>$11.1</td>
</tr>
<tr>
<td>10 Management</td>
<td>$1.2</td>
</tr>
<tr>
<td>11 Systems Engineering</td>
<td>$5.5</td>
</tr>
<tr>
<td>12 Product Assurance</td>
<td>$2.0</td>
</tr>
<tr>
<td>13 Integration and Test</td>
<td>$2.4</td>
</tr>
<tr>
<td>14 Total Payload Cost</td>
<td>$26.4</td>
</tr>
<tr>
<td>15 Payload NRE Cost</td>
<td>$11.5</td>
</tr>
<tr>
<td>16 Payload RE Cost</td>
<td>$14.9</td>
</tr>
<tr>
<td>17 Other NRE</td>
<td>$2.10</td>
</tr>
<tr>
<td>18 Spacecraft Bus Integration, Assembly, and Test</td>
<td>$0.26</td>
</tr>
<tr>
<td>19 Program Level</td>
<td>$0.57</td>
</tr>
<tr>
<td>20 Aerospace Ground Equipment</td>
<td>$1.27</td>
</tr>
<tr>
<td>21 Other RE</td>
<td>$8.27</td>
</tr>
<tr>
<td>22 Spacecraft Bus Integration, Assembly, and Test</td>
<td>$1.29</td>
</tr>
<tr>
<td>23 Program Level</td>
<td>$0.97</td>
</tr>
<tr>
<td>24 Launch Operations &amp; Orbital Support</td>
<td>$6.01</td>
</tr>
<tr>
<td>25 Fraction of Spacecraft Bus Cost RE/(RE+NRE)</td>
<td>52.6%</td>
</tr>
<tr>
<td>26 Total Upfront Cost</td>
<td>$47.45</td>
</tr>
<tr>
<td>27 Total NRE Cost</td>
<td>$14.89</td>
</tr>
<tr>
<td>28 TFU or T1 Cost</td>
<td>$24.95</td>
</tr>
<tr>
<td>29 Launch Cost</td>
<td>$7.62</td>
</tr>
</tbody>
</table>

The model predictions are derived from the Performance Requirements and Cost Model CERs
• The optical payload assumes diffraction limited optics

• Space system mass is proportional to the cube of the linear dimensions
  – Equivalent to saying that most spacecraft have about the same density

• Non-redundancy mass reduction factor
  – 5% reduction in estimated mass for every year the design life is reduced starting at 8 years (e.g., 10% for 6 yrs, 20% for 4 yrs, 30% at 2 yrs)

• All systems are designed using liquid propellant

• All missions are flown in a circular orbit

• All missions work at the same minimum working elevation angle of 30 deg

• Design life is proportional to altitude (e.g., 8 yrs at 800 km, 2 yrs at 200 km)

• Wright learning curve for multiple units after the TFU

• Costs postponed due to spacecraft being built and launched later are reduced to Present Value to account for the value of delayed spending
• **SmallSat Schedules** are much shorter than for traditional large satellites
  – Traditional major defense programs take 8.8 years in development (Milestone B) and well over 10 years from Milestone A to implementation [DoD Procurement Study]

• **Reliability** of **SmallSats** (including single string SmallSats) is essentially similar to that of traditional large satellites according to a Goddard study of over 1,500 spacecraft launched from 1995 to 2007

• **Risk** = the probability of a negative event times the impact/consequences of that event
  – Non-recurring cost for SmallSats is 1-2 orders of magnitude less than for traditional satellites
  – *Implementation Risk* is low due to low non-recurring cost and short schedule, i.e., the consequences of failing to implement a SmallSat system will not endanger the larger, more traditional system
  – *Operational Risk* of SmallSats is also much lower than traditional systems due to shorter operational life and the availability of spares (on orbit or on the ground) or back-up

• SmallSats also support the DoD objective of disaggregation

**SmallSat missions provide much shorter schedules, comparable reliability, and significantly less risk (both implementation and operational) than traditional large satellite missions.**
Cost vs. Cost Overruns

- **Cost overruns** are typically the primary concern for government acquisition
  - Cost overruns are a management problem associated with cost performance relative to expectations
  - Most easily resolved by reducing expectations
  - Makes sense programmatically, but not from the perspective of the end user
- **From the perspective of the end user, it is really cost vs. performance that matters**
  - How much performance can I get for how much money?
  - Equivalently, given the constraint of a limited total budget, how much performance am I able to achieve?
  - From this perspective, cost overruns are only relevant to the extent that they impact the overall cost vs. performance of the system
- **For operational programs on a system that is well understood (such as GEO communications), cost overruns are both important and bad**
  - For these systems costs should be well understood and well controlled
- **For R&D programs, some amount of cost overrun should be acceptable and expected**
  - If there are never any cost overruns, we’re not pushing hard enough on cost reduction

For purpose of creating much lower cost, high utility missions, cost (and schedule) for a given level of performance should be our measure of success, NOT cost overruns. This is a major purpose of creating Performance-Based Cost Modeling.
What Specifically will the Reinventing Space Project Do?

- **Near-term projects**
  - Support 3 USC graduate students doing fundamental research
    - We want to transform the current disaggregation/smallsat debate from a vague philosophical discussion to a quantitative discussion of costs and benefits
      - Extend traditional weight-based cost models to have mission utility factors to quantify, for example, the impact of microelectronics or composite materials
    - Provide seminars on Reinventing Space to anyone willing to listen
- **Longer-term projects**
  - More extensive basic technical research in cost reduction
  - Expand considerably the data base of cost reduction alternatives, based so far as possible on real experience throughout the community
  - Work with other universities to contribute to the solution of this long-term problem
  - Restart the *Journal of Reducing Space Mission Cost* for peer-reviewed contributions

Our goal is to start a more informed discussion of an inherently complex issue, starting today!
Where Are We Now?

- Currently teaching a USC graduate course, ASTE-523, in "Reinventing Space: the Design of Low-Cost Space Missions"
  - Have taught it every other year since 1998

- Have developed approximately 100 specific recommendations on dramatically reducing cost and schedule and preventing cost and schedule overruns
  - Process and programmatic
    - Attitude
    - Personnel
    - Government/Customer
    - Programmatic
  - Technology and Systems
    - Mission Design
    - Launch
    - Operations
    - Systems Engineering
    - Spacecraft Technology

- Are in the process of revising and expanding our database of approaches and methods and how they are presented

Dramatically reducing cost with high utility and robustness is not a simple process of discovering unobtainium. It is a complex mix of technology and processes tuned to the organization, the mission, and the needs of the end user – but history has shown that it can be done!
Summary of Lessons Learned

• Significantly reducing overall mission cost and schedule typically requires using multiple techniques that complement each other
  • Unless there is a single large cost or schedule driver, making a change in only one part of the system is unlikely to have a major impact on the system as a whole

• Reducing cost and schedule is not just a matter of finding a low-cost spacecraft bus or payload
  – It is a mission problem involving the full range of mission engineering issues in order to provide the end user the data they need, when they need it, at low cost and with high reliability

• Truly reducing overall space mission cost significantly will require at least some investment in, and development of both low-cost small spacecraft and low-cost, small, responsive launch systems

• The greatest impact comes from mission diversity
  – Small spacecraft used for some operational activities and as a test-bed to rapidly and economically develop low-cost processes and technology for larger missions

1. We want to reinvent space, but with the advantages of both modern technology and the experience base of 50 years of space exploration.

2. It takes real engineering to make it work, and that implies the need to start a proactive program that, in turn, needs to have support at the highest levels of management.