Probabilistic Mass Growth Uncertainties

Eric Plumer, NASA HQ
Darren Elliott, Tecolote Research Inc
Abstract

Mass has been widely used as a variable input parameter for Cost Estimating Relationships (CER) for space systems. As these space systems progress from early concept studies and drawing boards to the launch pad, their masses tend to grow substantially hence adversely affecting a primary input to most modeling CERs. Modeling and predicting mass uncertainty, based on historical and analogous data, is therefore critical and is an integral part of modeling cost risk.

This paper presents the results of a NASA on-going effort to publish mass growth datasheet for adjusting single-point Technical Baseline Estimates (TBE) of masses of space instruments as well as spacecraft, for both earth orbiting and deep space missions at various stages of a project’s lifecycle. This paper will also discuss the long term strategy of NASA Headquarters in publishing similar results, using a variety of cost driving metrics, on an annual bases. This paper provides quantitative results that show decreasing mass growth uncertainties as mass estimate maturity increases. This paper’s analysis is based on historical data obtained from the NASA Cost Analysis Data Requirements (CADRe) database.
Background

• NASA previously had no current repository of historical project data (programmatic, cost, and technical data)

• In 2004, NASA implemented a procedural requirement in NPR 7120.5 to conduct comprehensive programmatic data collections, called Cost Analysis Data Requirement (CADRe), at key milestones of a projects lifecycle

• Currently over 170 CADRe's have been captured and are available for us by NASA analysts to assess trends, identify cost/schedule behaviors, and obtain project specific insight

• As mass is a key parameter for NASA parametric model, a study was commissioned to use CADRe data to determine the historical observed growth for instruments from various points in the lifecycle
• CADRe is a three-part document that describes a NASA project at each major milestone (SRR, PDR, CDR, LRD, and End of Mission).

• PART A
  – Narrative project description in Word includes figures and diagrams that note significant changes between milestones.

• PART B
  – Excel templates capture key technical parameters to component-level Work Breakdown Structure (WBS), such as mass, power, and data rates.

• PART C
  – Excel templates capture the project’s cost estimate and actual life-cycle costs within NASA cost-estimating WBS to the project’s lowest WBS level.
# Frequency of CADRes

## Program Phases

<table>
<thead>
<tr>
<th>Flight Projects Life Cycle Phases</th>
<th>Pre-Phase A: Concept Studies</th>
<th>Phase A: Concept Development</th>
<th>Phase B: Preliminary Design</th>
<th>Phase C: Detailed Design</th>
<th>Phase D: Fabrication, Assembly &amp; Test</th>
<th>Phase E: Operations &amp; Sustainment</th>
<th>Phase F: Disposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional Waterfall Development or Directed Missions</td>
<td>Pre-Phase A: Concept Studies</td>
<td>Phase A: Concept Development</td>
<td>Phase B: Preliminary Design</td>
<td>Phase C: Detailed Design</td>
<td>Phase D: Fabrication, Assembly &amp; Test</td>
<td>Phase E: Operations &amp; Sustainment</td>
<td>Phase F: Disposal</td>
</tr>
<tr>
<td>AO-Driven Projects</td>
<td>Pre-Phase A: Concept Studies</td>
<td>Phase A: Concept Development</td>
<td>Phase B: Preliminary Design</td>
<td>Phase C: Detailed Design</td>
<td>Phase D: Fabrication, Assembly &amp; Test</td>
<td>Phase E: Operations &amp; Sustainment</td>
<td>Phase F: Disposal</td>
</tr>
</tbody>
</table>

## Formulation

- **Phase A**: Concept Development
- **Phase B**: Preliminary Design
- **Phase C**: Detailed Design

## Implementation

- **Phase D**: Fabrication, Assembly & Test
- **Phase E**: Operations & Sustainment
- **Phase F**: Disposal

## Legend

- **Mission Decision Review/ICR**: All parts of CADRe due ~30 days after site review
- **CADRe delivered; based on Concept Study Report (CSR) and winning proposal**: All parts of CADRe due ~30 days after PDR site review
- **CADRe, All Parts 90 days after launch, as built or as deployed configuration**: Update as necessary ~30 days after CDR
- **CADRe, update Part C only at the End of Planned Mission**: Update as necessary ~30 days after SIR (for larger flight projects)
Part A Example

Provides Descriptive Info of S/C and Payloads, etc
**Part B Example**

*Shows the Technical Data (Mass, Power)*

**System Level Tables**

**Payload Level Tables**

**Summary Tables**
Part C Example

Shows Cost data by WBS

<table>
<thead>
<tr>
<th>WBS Dictionary</th>
<th>Lifecycle Cost Estimate</th>
<th>Costs Mapped to the NASA WBS</th>
<th>WBS Dictionary</th>
</tr>
</thead>
</table>
CADRe Process

* One NASA Cost Engineering Database (ONCE)
Completed CADRe’s are Stored in ONCE

- NASA-certified Web-based system
- Controlled access
- Automated CADRe search and retrieval
Continuous Improvement by Creation and Maintenance of Analysis Products

**Today**
- 110 Instruments
- 200 CADRes

**Future**
- +30 CADRes/Yr
- +6 Missions/Yr

**Types of Analysis Products**
- One Pagers
- Datasheets
- Published Papers

**Analysis Trending**

**Bonus**
- Consistent Normalized Datasets

**Continuous Mass Growth Study**
- +2 additional Metrics

**Continuous Mass Growth Study**
- +1 additional Metric

**Consistent Normalized Dataset**
Study Hypothesis

- As the project nears the launch milestone, mass estimates increase in accuracy
  - Mean of the mass values by milestone approaches 1 (zero growth) –Getting better at predicting Launch Mass
  - Standard Deviation decreases as the mass technical baseline matures – Lower variability in mass range
- An Exponential Decay function can be used to model the average decrease in mass growth as the technical baseline matures
- Exponential Decay is a decrease in a value \( N \) according to the law \( N(x) = N_0 e^{-\lambda x} \) where:
  - \( \lambda \) is the decay constant
  - \( N_0 = N(0) \) is the initial value
Why Use Mass?

- **Data Availability**
  - Mass is a core technical parameter captured by CADRe

- **Data Usage**
  - Mass is widely used as a variable input parameter for Cost Estimating Relationships (CER) of space instruments
  - Underestimation of mass impacts CER results

- **Risk Input**
  - During development, mass is an estimate
  - “Final” mass may be different than what is estimated
  - Understanding growth potential allows for better quantification of risk inputs

Predicting instrument mass growth is critical and is an integral part of modeling instrument cost and its associated risk.
Study Process

- Assessment and evaluation of source data, extraction, normalization, and format conducted prior to data analysis

- Statistical Analysis software facilitates Growth Factor and Decay analysis – used COTS tools (Excel and CO$TAT from ACEIT Software suite)

- Data Stratifications include selection of Milestone groups or technical characteristics of dataset instruments
Analysis Framework

Data Collection

Growth Factor Analysis

Decay Analysis

Consolidated Datasheet

Formatted Analysis Worksheets

Presented at the 2013 ICEAA Professional Development & Training Workshop - www.iceaaonline.com
Calculation Techniques

• **Milestone Growth Factors**
  – Growth factors for mass developed for each mission from each milestone to final launch value
  – Two techniques used
    • Technique 1: CDF development and mean value determination from Excel
    • Technique 2: Distribution and statistics determined from CO$TAT$ best-fit analysis

• **Decay Equation**
  – Identify a group of instruments with data across all targeted milestones
  – Determine mean growth factors for each milestone
  – Conduct regression analysis
    • Excel using graphing capability
      – Plot chart of Mean Percentage Growth
      – Run exponential regression through points and display equation
    • Excel using a formula
      – INDEX(LINEST(LN(MEAN PERCENTAGE GROWTH VALUES),ESTIMATE MATURITY),1)
    • CO$TAT$ using Non-linear analysis feature
      – Estimate Maturity = a * EXP(b* Mean Percentage Growth)
      – Calculate decay constant = b
Decay Analysis Results Can be Used to Create a Continuous Mass Growth Model

Basic Model

Instrument Mass Growth

\[ M_{Adj} \equiv M \left( e^{-bt} \left(K_{GF} - 1\right) + 1 \right) \]

- \( M_{Adj} \) = Growth-adjusted Mass Estimate Distribution
- \( K_{GF} \) = Baseline (@ CSR) Mass Estimate Growth Factor Distribution
- \( M \) = Technical Baseline Point Estimate of Mass
- \( b \) = Mass Growth Decay Constant
- \( t \) = Estimate Maturity Parameter

(CSR/SRR = 20%; SDR=40%; PDR=60%; CDR=80%; Launch=100%)

Enables Analysts to Use at any Point in Design Cycle and not just at Milestones
Deriving a Decay Constant from Mass Growth Data

\[ y = 0.42e^{-2.174x} \]

\[ R^2 = 0.84 \]

Decay Constant

2.174
Example of Continuous Mass Growth Decay Model

Enhances Analyst Capability to Specify Mass Uncertainty Ranges for CERs and SERs
Mass Growth Distributions
Common Milestones – CADRe Data
Percent Growth by Milestone
Common Milestones – CADRe Data

Scenario 1

<table>
<thead>
<tr>
<th></th>
<th>CSR/SRR</th>
<th>PDR</th>
<th>CDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>185%</td>
<td>118%</td>
<td>33%</td>
</tr>
<tr>
<td>Q3</td>
<td>59%</td>
<td>27%</td>
<td>11%</td>
</tr>
<tr>
<td>Mean</td>
<td>38%</td>
<td>14%</td>
<td>6%</td>
</tr>
<tr>
<td>Median</td>
<td>39%</td>
<td>12%</td>
<td>3%</td>
</tr>
<tr>
<td>Q1</td>
<td>3%</td>
<td>-1%</td>
<td>0%</td>
</tr>
<tr>
<td>Min</td>
<td>-64%</td>
<td>-88%</td>
<td>-19%</td>
</tr>
</tbody>
</table>

Presented at the 2013 ICEAA Professional Development & Training Workshop - www.iceaaonline.com
Mass Growth Decay Model

Common Milestones – CADRe Data

Decay Constant
2.187

\[ y = 0.4049e^{-2.187x} \]

\[ R^2 = 0.9341 \]

CSR/SRR = 0%; SDR = 40%; PDR = 60%; CDR = 80%; Launch = 100%
Next Steps

• Finalize Study Results
  – General results for all NASA instruments and Spacecraft
  – Segmentation analysis (e.g., instrument type, destination)

• Publish one-pager fact sheets to help NASA analysts in the field