Probabilistic Mass Growth Uncertainties

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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 discusses 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 project's lifecycle
- Currently over 170 CADRes 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

- 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

<table>
<thead>
<tr>
<th>Program Phases</th>
<th>Formulation</th>
<th>Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flight Projects Life Cycle Phases</strong></td>
<td><strong>Pre-Phase A: Concept Studies</strong></td>
<td><strong>Phase A: Concept Development</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Traditional Waterfall Development or Directed Missions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>AO-Driven Projects</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 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
- **Update as necessary ~30 days after CDR**
- **Update as necessary ~30 days after SIR (for larger flight projects)**
- **CADRe, All Parts 90 days after launch, as built or as deployed configuration**
- **CADRe, update Part C only at the End of Planned Mission**
Part A Example

Provides Descriptive Info of S/C and Payloads, etc

System Overview

Subsystem Description

Payload Description

Project Management
Part B Example

Shows the Technical Data (Mass, Power)

### System Level Tables

<table>
<thead>
<tr>
<th>Payload</th>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>45 kg</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>35 W</td>
<td></td>
</tr>
</tbody>
</table>

### Payload Level Tables

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>45 kg</td>
</tr>
<tr>
<td>Power</td>
<td>35 W</td>
</tr>
</tbody>
</table>

### Summary Tables

<table>
<thead>
<tr>
<th>System</th>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
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<td></td>
</tr>
<tr>
<td>Power</td>
<td>35 W</td>
<td></td>
</tr>
</tbody>
</table>

### Key Technical Parameters

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
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<tr>
<td>Power</td>
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</tr>
</tbody>
</table>
Part C Example

Shows Cost data by WBS

Lifecycle Cost Estimate

Costs Mapped to the NASA WBS

WBS Dictionary
CADRe Process

Contractor

PM Cost Repository

NASA Accounting Database

PM’s Systems Engineering Repository

Project Manager

Cost estimates & actuals

MD Reviews

CAD Accepts & Stores

CADRe Developer

Cost estimates & actuals

PA&E/CAD Reviews

* One NASA Cost Engineering Database (ONCE)

Government Users
Completed CADRe’s are Stored in ONCE

- NASA-certified Web-based system
- Controlled access
- Automated CADRe search and retrieval
CADRe/ONCE Analysis Product Evolution

Today
110 Instruments
200 CADRes

Initial Mass Growth Study

Enhanced Mass Growth Study
+ 1 additional Metric

Trending on Mass Growth
+ 2 additional Metrics

Continuous Trending
Additional Metrics
Normalized Dataset

Future
+30 CADRes/Yr
+6 Missions/Yr

Types of Analysis Products
One Pagers
Datasheets
Published Papers

Bonus
Analysis Trending

Bonus
Consistent Normalized Datasets

Continuous Improvement by Creation and Maintenance of Analysis Products
• 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
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.
• 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

Power Mass TRL...

Growth Factor

\[ y = 0.3386e^{-2.021x} \]

\[ R^2 = 0.9585 \]

\[ \text{Percentage Growth} \]

\[ \text{Maturity Data Point} \]

\[ \text{Mean Decay Expon. (Mean Decay)} \]

\[ \begin{array}{|c|c|c|c|}
\hline
\text{Observations} & \text{CSR} & \text{PDR} & \text{CDR} \\
\hline
1 & 0.568 & 0.65952356 & 0.609458723 \\
2 & 0.84 & 0.75466067 & 0.582333333 \\
3 & 1.207752206 & 1.091353459 & 0.994825249 \\
4 & 1.530714286 & 1.127719403 & 1.09709401 \\
5 & 1.862791286 & 1.127719403 & 1.09709401 \\
6 & 0.574879272 & 0.549099091 & 1 \\
7 & 0.357142857 & 0.123 & 1 \\
8 & 0.357142857 & 0.84 & 1 \\
9 & 2.566046512 & 1.754161106 & 1.025429553 \\
10 & 1.425023788 & 0.951512012 & 1.025429553 \\
11 & 0.75466067 & 0.75466067 & 0.582333333 \\
12 & 0 & 0 & 0 \\
13 & 1.379239427 & 1.125414126 & 0.97154781 \\
14 & 1.207752206 & 1.091353459 & 0.994825249 \\
15 & 0 & 0 & 0 \\
16 & 0 & 0 & 0 \\
17 & 0 & 0 & 0 \\
18 & 0 & 0 & 0 \\
19 & 0 & 0 & 0 \\
20 & 0 & 0 & 0 \\
\hline
\end{array} \]
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**

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

\( M_{\text{Adj}} = \) 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

<table>
<thead>
<tr>
<th>Sample</th>
<th>LogNormal</th>
<th>Normal</th>
<th>Triangular</th>
<th>Beta</th>
<th>Uniform</th>
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</thead>
<tbody>
<tr>
<td>Mean</td>
<td>1.3787</td>
<td>1.3800</td>
<td>1.3788</td>
<td>1.3800</td>
<td>1.3787</td>
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<tr>
<td>StDev</td>
<td>0.5399</td>
<td>0.5209</td>
<td>0.5209</td>
<td>0.5099</td>
<td>0.5003</td>
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<tr>
<td>CV</td>
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<td>0.3804</td>
<td>0.3994</td>
<td>0.3776</td>
<td>0.3643</td>
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<tr>
<td>Min</td>
<td>0.3571</td>
<td>0.2284</td>
<td>0.2284</td>
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<tr>
<td>Mode</td>
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<td>1.3787</td>
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<tr>
<td>Max</td>
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<td>2.7055</td>
<td>2.7055</td>
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<tr>
<td>Alpha</td>
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<td>5.9756</td>
<td>5.9756</td>
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<tr>
<td>Beta</td>
<td>29.9904</td>
<td>29.9904</td>
<td>29.9904</td>
<td>29.9904</td>
<td>29.9904</td>
</tr>
</tbody>
</table>

Data Count: 46
% < 0 = 0

Standard Error of Estimate: 0.0949

PDR

CDF

CSR/SRR

PDR

CDR

LogNormal (3) — Normal (4) — Triangular (1) — Beta (2) — Uniform (5)
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>
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