A Software Tool for CubeSat Mission
Risk Estimating Relationships

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- Labs located on campus in WRW building, 4th floor
- Entirely student-led with a faculty PI (Dr. Glenn Lightsey)
- Current flight experience:
  - FASTRAC nanosatellite (25 kg each), still operational, launched in Nov. 2010
  - Bevo-1/Paradigm (1U) launched in July 2009
- On the horizon:
  - RACE (3U) w/ JPL
    - Delivered spacecraft bus for radiometer mission, Mar 2014
    - To be flown via NanoRacks, October 2014
  - Bevo-2 (3U) w/ NASA-JSC & Texas A&M
    - Delivery to NASA in June 2014
    - To be flown via NanoRacks
  - ARMADILLO (3U) w/ Baylor University
    - University Nanosatellite Program winner, Jan. 2013
    - Selected for ELaNa in Spring 2012 (to be manifested)
  - INSPIRE (3U) w/ JPL
    - Providing thruster; collaboration with other organizations
    - To be flown on interplanetary trajectory
Talk Overview

- **CubeSat Mission Risk Survey – Results!**
  - Risk Analysis Tool
    - Mathematical overview
    - Tool overview
    - How to obtain a copy (Feedback wanted!)
  - Decision Advisor

Six main survey areas:
1. Demographics
2. Schedule Risk
3. Payload Risk
4. Spacecraft Risk – comm, basic health data, standards
5. Personnel & Management Risk
6. Cost Risk
Survey Data Results

- THANK YOU!
- Collected responses April – November 2013
- 65 CubeSat responses
- 52 unique and valid missions used for high-level analysis
- 3 outliers were removed for regression analysis
Survey Risk Results

Top Ten Risk Events as identified by survey responses:

1. Software design delay
2. Attrition or turnover of team members
3. Mechanical design delay
4. Incomplete understanding of the projected total mission cost
5. Inability to find desired spacecraft components
6. Sudden loss of crucial team members
7. Delay due to inadequate documentation
8. Loss of information
9. Lack of sufficient training for team members completing flight qualification necessary tasks
10. Delay due to issues with payload provider

All events in the top ten have to do with personnel, schedule, or cost
Risk Tool – Mathematical Overview

- Used General Error Regression, Minimum Percentage Error – Zero Percentage Bias (MPE-ZPB)
  - Similar regression method used by USCM and SSCM cost models
  - Comparable to Least Squares, but multiplicative error
- 12 Function Forms tested
- Used Excel VBA and Solver
### Factors of interest in regression analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Input</th>
<th>Actual or Predicted?</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form factor</td>
<td>3</td>
<td></td>
<td>Enter a numeric value corresponding to the number of U's your spacecraft design uses (e.g. 3U would be entered as &quot;3&quot;)</td>
</tr>
<tr>
<td>Mass</td>
<td>4</td>
<td></td>
<td>Enter a numeric value of the mass limit (in kg)</td>
</tr>
<tr>
<td>No, but we have a launch promised</td>
<td></td>
<td></td>
<td>Select an answer using the drop-down menu: Yes, the s/c has launched; No, but we've been manifested; No, but we have a launch promised (ELaNa or similar); No, we have not been manifested or given a promise of a launch</td>
</tr>
<tr>
<td>Launch Date</td>
<td>2014</td>
<td></td>
<td>Enter the date of the launch; if the s/c has yet to be launched, give the projected date. (Can be in MM/DD/YYYY or MM/YYYY or YYYY format)</td>
</tr>
<tr>
<td>Months in Development</td>
<td>7 Actual</td>
<td></td>
<td>Enter a numeric value corresponding to the number of months in s/c design and development, including everything up until flight integration; indicate whether this value is actual or predicted</td>
</tr>
<tr>
<td>Months in Integration</td>
<td>4 Actual</td>
<td></td>
<td>Enter a numeric value corresponding to the number of months taken for s/c integration; indicate whether this value is actual or predicted</td>
</tr>
<tr>
<td>Months in S/C Functional Testing</td>
<td>7 Predicted</td>
<td></td>
<td>Enter a numeric value corresponding to the number of months spent on integrated s/c testing at the organization level, including functional testing; indicate whether this value is actual or predicted</td>
</tr>
<tr>
<td>Months in S/C Environmental Testing</td>
<td>5 Predicted</td>
<td></td>
<td>Enter a numeric value corresponding to the number of months spent on necessary testing to satisfy launch preparation, prethermal, etc., and marginal value is actual or predicted</td>
</tr>
<tr>
<td>Months S/C is awaiting launch</td>
<td>3 Predicted</td>
<td></td>
<td>Enter a numeric value corresponding to the number of months the spacecraft was &quot;on the shelf&quot; waiting for the next launch; indicate whether this value is actual or predicted</td>
</tr>
<tr>
<td>Months S/C is in operations</td>
<td>6 Predicted</td>
<td></td>
<td>Enter a numeric value corresponding to the number of months the spacecraft was operational in orbit; indicate whether this value is actual or predicted</td>
</tr>
<tr>
<td>Milestone</td>
<td>LVINT</td>
<td></td>
<td>Enter the name of the milestone for which these numbers reflect the status of the project.</td>
</tr>
</tbody>
</table>

### Macro buttons will calculate the L-C values for multiple milestones

- Calculate L-C values for Milestone 1
- Calculate L-C values for Milestone 2
- Calculate L-C values for Milestone 3

### Indicate whether values are actual or predicted
Risk Tool V1.1 – Outputs Page

Mission risk L-C values calculated via rank reciprocal weighting scheme (see JoSS paper)

Root causes calculated via VBA-programmed functions

Currently up to 3 milestones can be tracked at one time
Risk Tool V1.1 – Plots Page

Ability to choose which milestones or risks are plotted

Ability to bring desired risk to front

Rank reciprocal weighted mission risks (same as on outputs page)

Ability to clear plot and reset options
# Risk Tool V1.1 – Equations Pages

## Consequence Coefficients

<table>
<thead>
<tr>
<th>Mission Risk</th>
<th>Root Cause</th>
<th>Consequence Formula</th>
<th>Consequence Formula</th>
<th>Consequence Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schedule</td>
<td>Inability to find desired spacecraft components</td>
<td>$L_3 = a + b \cdot ff + cc \cdot launch$</td>
<td>$a = 3.854$</td>
<td>$b = -0.29$</td>
</tr>
<tr>
<td></td>
<td>Mechanical design delays (such as issues with the CAD or drawings)</td>
<td>$T_2 = a + b \cdot dev^cc + d \cdot int^e + f \cdot scfunc^g + h \cdot environ^i + j \cdot wait^k + l \cdot ops^m$</td>
<td>$a = 10$</td>
<td>$b = -231$</td>
</tr>
<tr>
<td></td>
<td>Software design delays (such as basic component functionality or embedded coding issues)</td>
<td>$L_2 = a + b \cdot ff + cc \cdot dev + d \cdot int + e \cdot scfunc + f \cdot environ + g \cdot wait + h \cdot ops$</td>
<td>$a = 2$</td>
<td>$b = 2.973$</td>
</tr>
<tr>
<td></td>
<td>Delay due to issue with payload provider (may be related to delivery of EDU or flight unit, documentation, or interface issues)</td>
<td>$L_3 = a + b \cdot ff + cc \cdot launch$</td>
<td>$a = 3.107$</td>
<td>$b = -0.04$</td>
</tr>
<tr>
<td></td>
<td>Delay due to inadequate documentation</td>
<td>$T_2 = a + b \cdot dev^cc + d \cdot int^e + f \cdot scfunc^g + h \cdot environ^i + j \cdot wait^k + l \cdot ops^m$</td>
<td>$a = 10$</td>
<td>$b = -38.7$</td>
</tr>
<tr>
<td>Payload</td>
<td>Software interface issues between payload and spacecraft bus</td>
<td>$L_2 = a + b \cdot ff + cc \cdot dev + d \cdot int + e \cdot scfunc + f \cdot environ + g \cdot wait + h \cdot ops$</td>
<td>$a = 2.489$</td>
<td>$b = 0.175$</td>
</tr>
<tr>
<td></td>
<td>Hardware/electrical interface issues between payload and spacecraft bus</td>
<td>$L_2 = a + b \cdot ff + cc \cdot dev + d \cdot int + e \cdot scfunc + f \cdot environ + g \cdot wait + h \cdot ops$</td>
<td>$a = 2.312$</td>
<td>$b = -0.03$</td>
</tr>
<tr>
<td></td>
<td>Payload malfunction due to mechanical issues</td>
<td>$L_5 = a + b \cdot dev + cc \cdot int + d \cdot scfunc + e \cdot environ + f \cdot wait + g \cdot ops$</td>
<td>$a = 5.350$</td>
<td>$b = -0.0$</td>
</tr>
<tr>
<td></td>
<td>Payload malfunction due to software issues</td>
<td>$L_2 = a + b \cdot ff + cc \cdot dev + d \cdot int + e \cdot scfunc + f \cdot environ + g \cdot wait + h \cdot ops$</td>
<td>$a = 2.319$</td>
<td>$b = 0.113$</td>
</tr>
</tbody>
</table>
Risk Tool – Obtain & Feedback

To obtain a FREE copy of the tool AND leave feedback on how to improve it:
https://sites.google.com/site/brumbaughresearch/research/risk-analysis-tool

http://goo.gl/8hpPiz
(A) Obtain Risk Analysis Tool

To obtain a copy of the Risk Analysis Tool, please fill out the following form. You will then be contacted with a copy of the tool. For a description of how to use the tool as well as a discussion of the mathematical methods behind the tool, please read the User's Guide.

Request for CubeSat Risk Tool

In order to keep track of user demographics, please fill out the following information. Once the response is received, I will contact you with instructions on how to access the tool.

* Required

What is your name? *

What is your email address? *

What organization are you with? *

University, company, etc.

What is the name of your CubeSat mission?

http://goo.gl/8hpPiz
(B) Risk Tool Feedback

Please provide any feedback you have in using the Risk Analysis Tool. Any comments and suggestions will be considered for implementation in future iterations of the tool.

CubeSat Risk Analysis Tool Feedback

Thank you for using this tool! We would appreciate any and all feedback -- constructive feedback and bug reports! Please submit your thoughts using the boxes below. Please contact me with any urgent issues at katharine.brumbaugh gamble@gmail.com.

No response is mandatory, but as much detail as you are able to provide is helpful.

For more information on this research, please visit https://sites.google.com/site/brumbaughresearch/

How useful was this tool for your analysis purposes?

1 2 3 4 5 6 7 8 9 10

Not at all • • • • • • • • Very helpful

What would you like to see in the next iteration of this tool?

http://goo.gl/8hpPiz
Schedule risk - the event of a slip in meeting schedule milestones or deadlines that could be caused by any number of things. The five root causes identified here were used in the gathering of survey data.

Excel highlights the technique which maximizes the utility function and places the results under the RC branch.
Final Thoughts…

• Thank you for submitting your risk data!

• Check out research website
  – Publications list
  – More survey data analysis
  – More descriptions and details of research (risk analysis and decision advisor tools)

• The risk analysis tool was designed for your use – PLEASE use it, and let me know how it works!

https://sites.google.com/site/brumbaughresearch/research/risk-analysis-tool
Back-Up Slides
### Survey Analysis Results

**Summarized additional SCH issues:**
- Delayed launch: manifest change, launch vehicle and primary payload schedule slip
- Student workforce issues: time commitment and turnover rate
- Electronics design delay
- Funding delays: sequestration, grants, internal funding fluctuations
- Payload development delay: when internal and external
- Change in providers
- Contract delays
- Re-scoping / de-scoping mission goals
- Environmental/Spacecraft testing delay
- Political disagreement: quality assurance measures, funding, poor management, and resistance of program

**Summarized additional SC issues:**
- Lack of proper requirements and testing at the subsystem level
- Unknown loss of contact

**Summarized additional PER issues:**
- Lack of resources: small team size, poor distribution of resources
- Lack of professionalism: students treating project as partial credit, poor documentation
- Distributed locations of personnel yields communication and management issues
- Loss of information and pace when lose team members
- Lack of institution support and resources
- Many people involved implies lots of management overhead
- ITAR regulations

**Summarized additional PAY issues:**
- New technology unknowns
- Environmental concerns: test early and often to avoid late-stage mitigation (EMI/EMC)
- To buy or develop a payload was more expensive than anticipated
- Legal issues surrounding licensing
- Software design and testing: suggest using interface emulators

**Summarized additional COST issues:**
- Poor/last minute travel planning
- Poor initial cost planning
- Cost of professional engineer reviews
- Needed additional equipment after unforseen hardware issues
- Additional hardware iterations
- Changing requirements/contractors midway through design
- Finding and obtaining funding
- Unexpected increase in payload/contracted development costs
Summarized personnel requirements to be on the team:

- Application and interview process; Peer review process; peer recruitment
- Students paid, get school credit, or volunteer; Time commitment requirement
- US citizenship required; ITAR compliance
- Minimum GPA requirement
- Students keep logs of their progress
- Class standing requirement; full-time student
- Industry - relevant experience required; degree requirements
- Industry - selected by open competitions

General Suggestions:

- Biggest CubeSat issue is managing personnel change
- Push for early development on a fully built, flight-like, engineering model -- this allows for faster integration and testing of flight units
**Regression Approach**

**Input:**
Variables of interest:
- Form factor
- Life cycle times
- Launch indicator

**Calculated:**
Regression techniques to minimize desired element(s):
- Sum of squared deviations
- Sum of error of the estimate
- Bias

\[ SSD_M = \sum_{i=1}^{n} \left( \frac{y_i - f(x_i, a)}{f(x_i, a)} \right)^2 \]

\[ B_M = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{f(x_i, a) - y_i}{f(x_i, a)} \right) \]

**Output:**
Relationship between input variables and risk likelihood and consequence values:
\[ Y(X) = a \times x_1^b + c \times x_2^d + ... \]
## Additive vs. Multiplicative Models

<table>
<thead>
<tr>
<th></th>
<th>Additive</th>
<th>Multiplicative</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Function form</strong></td>
<td>$y_i = f(x_i, \tilde{a}) + \varepsilon_i$</td>
<td>$y_i = f(x_i, \tilde{a}) \varepsilon_i$</td>
</tr>
<tr>
<td><strong>Sum of Squared Deviations (SSD)</strong></td>
<td>$SSD_A^2 = \sum_{i=1}^{n} (y_i - f(x_i, a))^2$</td>
<td>$SSD_M^2 = \sum_{i=1}^{n} \left( \frac{y_i - f(x_i, a)}{f(x_i, a)} \right)^2$</td>
</tr>
<tr>
<td><strong>Standard Error of Estimate (SEE)</strong></td>
<td>$SEE_A = \sqrt{\frac{1}{n-m} \sum_{i=1}^{n} (y_i - f(x_i, a))^2}$</td>
<td>$SEE_M = \sqrt{\frac{1}{n-m} \sum_{i=1}^{n} \left( \frac{y_i - f(x_i, a)}{f(x_i, a)} \right)^2}$</td>
</tr>
<tr>
<td><strong>Bias</strong></td>
<td>$B_A = \frac{1}{n} \sum_{i=1}^{n} (f(x_i, a) - y_i)$</td>
<td>$B_M = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{f(x_i, a) - y_i}{f(x_i, a)} \right)$</td>
</tr>
</tbody>
</table>

- **Additive Model**: Tends to favor larger values because of larger errors.
- **Multiplicative Model**: Reduces influence of large data values.

Use of General Error Regression (GER) will allow for use of either additive or multiplicative error models. Additionally, all function forms are available, as opposed to OLS methods where really only linear functions may be used.
Background: Regression Analysis

- Given a set of data, regression analysis finds the line of best fit to describe the data
- Regression techniques include:
  - Ordinary Least Squares
    - Traditionally used for linear models and additive models
    - Minimizes square standard error
  - General Error Regression Techniques:
    - Can use additive or multiplicative functions.
    - Minimum Percentage Error (MPE)
    - Iterated Least Squares / Minimum Unbiased Percentage Error (IRLS / MUPE)
    - Minimum Percentage Error – Zero Percentage Bias (MPE-ZPE)

“Lottery” System to Obtain U-Values

<table>
<thead>
<tr>
<th>What is the maximum amount of money you are willing to spend?</th>
<th>$2,500.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>What is the maximum number of people you are willing to allocate to a mitigation technique?</td>
<td>5</td>
</tr>
<tr>
<td>What is the maximum number of days you are able to spend on a mitigation technique?</td>
<td>40</td>
</tr>
</tbody>
</table>

If you had a 50-50 chance at losing $0 or losing $2,500, what monetary value would you say is equivalent? Choose a value from the 'Value Outcomes table' and place it underneath the 'X'.

<table>
<thead>
<tr>
<th>Value outcomes</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>A $0.00</td>
<td></td>
</tr>
<tr>
<td>B $250.00</td>
<td></td>
</tr>
<tr>
<td>C $500.00</td>
<td></td>
</tr>
<tr>
<td>D $750.00</td>
<td></td>
</tr>
<tr>
<td>E $1,000.00</td>
<td></td>
</tr>
<tr>
<td>F $1,250.00</td>
<td></td>
</tr>
<tr>
<td>G $1,500.00</td>
<td></td>
</tr>
<tr>
<td>H $1,750.00</td>
<td></td>
</tr>
<tr>
<td>I $2,000.00</td>
<td></td>
</tr>
<tr>
<td>J $2,250.00</td>
<td></td>
</tr>
<tr>
<td>K $2,500.00</td>
<td></td>
</tr>
</tbody>
</table>

If you had a 50-50 chance at losing $0 or losing $1,000, what monetary value would you say is equivalent? Choose a value from the 'Value Outcomes table' and place it underneath the 'Y'.

If you had a 50-50 chance at losing $0 or losing $1,250, what monetary value would you say is equivalent? Choose a value from the 'Value Outcomes table' and place it underneath the 'Z'.

“Lotteries” are used to obtain user preferences. Using several different lottery systems will ensure consistent results.
### Joint Utility Curve – Scaling Factors

<table>
<thead>
<tr>
<th>Outcome</th>
<th>$u(1,1,1)$</th>
<th>$u(0,0,0)$</th>
<th>$u(0,1,0)$</th>
<th>$u(1,0,0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;\text{cost at best, people at best, time at best}&gt;$</td>
<td>0.5</td>
<td>0.5</td>
<td>0.9</td>
<td>0.1</td>
</tr>
<tr>
<td>$&lt;\text{cost at worst, people at best, time at worst}&gt;$</td>
<td>0.9</td>
<td>0.9</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$&lt;\text{cost at worst, people at worst, time at best}&gt;$</td>
<td>0.1</td>
<td>0.1</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

- $E[u] = 1$ for $u(1,1,1)$
- $E[u] = 0$ for $u(0,0,0)$

**What probability, $p$, would make you indifferent between having $<\text{cost at worst, people at best, time at worst}>$ or the $p$ probability of all attributes at their best and a $(1-p)$ probability of all attributes at their worst?**

- $u(1,0,0) \approx 0.5 u(0,0,0)$

**What probability, $p$, would make you indifferent between having $<\text{cost at best, people at best, time at best}>$ or the $p$ probability of all attributes at their best and a $(1-p)$ probability of all attributes at their worst?**

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**What probability, $p$, would make you indifferent between having $<\text{cost at worst, people at worst, time at best}>$ or the $p$ probability of all attributes at their best and a $(1-p)$ probability of all attributes at their worst?**

- $u(0,0,1) \approx 0.5 u(0,0,0)$

**Scaling constants must satisfy:**

$$1 + k = (1 + kk_1)(1 + kk_2)(1 + kk_3)$$

- $k$ is determined by implicitly solving the equation given the $k_i$ values obtained from the elicitation method.
Joint Utility Function

- Once scaling constants have been found, may combine marginal utility functions with:

\[ 1 + k u(x_1, x_2, x_3) = (1 + k_1 u_1(x_1))(1 + k_2 u_2(x_2))(1 + k_3 u_3(x_3)) \]

- Rescale the values to be between 0 and 1, with:
  - \( U(\text{cost} = \text{min}, \text{people} = \text{min}, \text{time} = \text{min}) = 1 \rightarrow U(1,1,1) \)
  - \( U(\text{cost} = \text{max}, \text{people} = \text{max}, \text{time} = \text{max}) = 0 \rightarrow U(0,0,0) \)

\[ u' = \frac{u - u(0,0,0)}{u(1,1,1) - u(0,0,0)} \]

- Assumptions:
  - Three attributes fully characterize decision maker’s preference system: cost, people, time required for a given mitigation technique
  - Preferential independence \( \rightarrow \) tradeoffs between any two attributes governed by unique indifference relationship independent of other attribute
  - Utility independence \( \rightarrow u_i(x_i) \) is independent of all other \( x_j \neq i \)
Joint Utility Function

- Example joint function with people = 3: