Cost Considerations for Estimating SmallSat I&T

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***Abstract*—**In the early phases of project formulation, mission integration and test (I&T) costs are typically estimated via a wrap factor approach, analogies to similar missions adjusted for mission specifics, or a Bottom Up Estimate (BUE). The wrap factor approach estimates mission I&T costs as a percentage of payload and spacecraft hardware costs. This percentage is based on data from historical missions, with the assumption that the project being estimated shares similar characteristics with the underlying data set used to develop the wrap factor. This technique has worked well for traditional spacecraft builds since typically as hardware costs grow, I&T test costs do as well. However, with the emergence of CubeSats and nanosatellites, the cost basis of hardware is just not large enough to use the same approach. This suggests that there is a cost "floor" that covers basic I&T tasks, such as a baseline of labor and testing.

This paper begins the process of developing a parametric model for estimating Small Satellite (SmallSat) Integration & Test (I&T) costs. Parametric models are a result of a cost estimating methodology using statistical relationships between historical costs and other program variables to develop cost estimating relationships (CERs). The objective is to generate a CER equation to show a relationship between the dependent variable, cost, to one or more independent variables. We will use the results of this analysis to develop a CER that can be used to better predict SmallSat I&T costs.

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1. INTRODUCTION

When we look at constellations of SmallSats, we begin to see cost sharing between SmallSats in the same constellation. With the evolution of new technologies, the way we estimate costs needs to evolve as well. Our research will examine approaches to estimating I&T costs when the base hardware cost is much lower than a traditional space science mission, making historical wrap factors inapplicable. Since SmallSats are generally simpler, less complex, and cheaper hardware, the cost of integrating multiple identical hardware elements isn't accurately reflected.

We drew motivation from and leveraged previous work looking at I&T costs for historical APL robotic missions[1]. The missions in that analysis were all New Frontiers, Discovery, or NASA directed missions. Thus, they have large hardware bases. A lognormal curve fits the APL I&T data with an R^2 of 97%, meaning 97% of the variation in the dependent variable can be attributed to the independent variable. The CER for I&T is $y = 30{,}805\ln(x) - 69{,}164$ where x is the total number of points of integration (discussed in more detail below) calculated for the mission that is being estimated and y is predicted I&T costs in FY15$K.

We ran small satellite missions through this CER. For single unit satellite missions, this CER underestimates by an average prediction error of -708%. For multiple unit satellite missions, this CER overestimates by an average prediction error of 912%. Our research aims to develop a specific SmallSat CER that can better predict SmallSat I&T costs for missions with smaller hardware bases.

2. GROUND RULES AND ASSUMPTIONS

The NASA Cost Analysis and Data Requirements (CADRe) database was used to discover SmallSat NASA missions. CADRe is a three part document that records important data and specifications for a NASA project at each lifecycle milestone. Part A describes the project; part B contains key technical parameters such as mass, power, instrument types, etc.; and part C captures the NASA project's cost estimate.

We also looked at internal records for Department of Defense (DoD) and grant missions. Because we were only able to obtain data for one NASA grant mission and one DoD mission, these missions were excluded from the analysis. Thus, the undermentioned models should only be used for Class D NASA missions.

3. METHODOLOGY

Mass and cost data was collected via CADRe, parts B and C respectively. Using CADRe-only data provided a standard

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[1] Powers, N. "Analysis of Integration and Test (I&T) Costs for Recent NASA Missions." AIAA/San Diego Aerospace Conference, 2014.

format for the data points collected. We focused on missions with total hardware, payload and spacecraft, mass of less than 180 kilograms per small satellite[2]. Our dataset is comprised of two single spacecraft missions and three multiple-spacecraft missions as seen in Table 1. The NASA New Start Inflation Index was used to normalize real-year cost data into FY$21. For purposes of this paper, costs for I&T include integration of the spacecraft subsystems and instruments. Available data was normalized accordingly.

Table 1. Missions in Analysis

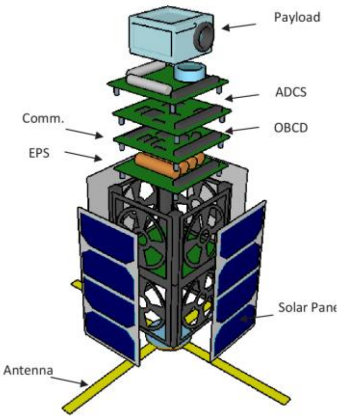
Mission	# of SC
Mission 1	1
Mission 2	5
Mission 3	1
Mission 4	8
Mission 5	6

With the objective being to develop a parametric CER that calculates I&T costs for small satellites, all of the variables in Table 2 were considered. Due to a limited dataset, finding meaningful statistical relationships was difficult. For example, we believe risk classification could be a statistically significant variable. However, all of the missions in this analysis are the same risk class. After exploring all of the variables, we chose to focus on points of integration due to it being the best predictor and due to previous success.

Table 2. Potential Parameters

Parameters	
Mission Destination	Mission Duration
Number of Cubesat/Smallsat	Development Duration
Launch Year	Bus Provider (Custom vs COTS)
Total Mission Cost	Number of Instruments
Total HW Cost	Risk Classification
Total I&T Cost	Number of I&T Requirements
Who Did I&T	Points of Integration

Figure 1.



For the purposes of this paper, points of integration are defined as the total number of instruments and spacecraft subsystems excluding flight software. Each spacecraft subsystem is treated as one point of integration regardless of the number of separately integrated parts the subsystem may contain. For example, if we have a SmallSat mission with one unit having six spacecraft subsystems and a one instrument payload (seen in Figure 1), the points of integration for one unit (P_{sc}) would be seven: 6+1=7.

To calculate the points of integration for multiple units, we came up with two different calculations:

1. First, we looked at **total** points of integration. Let

   P_{SC} = total points of integration;
   K = number of units;
   then,

   (1) $P_{tot} = P_{sc} * K$

   If there are four SmallSats of the aforementioned example mission, the calculation is as follows:

   P_{tot} = 7,
   K = 4,

   P_{tot} = 7 * 4 = 28

2. We also looked at **weighted** points of integration. We know that there is an average of 23% I&T savings per additional unit based on industry data. Instead of simply using the number of units as a multiplier, we apply these savings to come up with a weighted number. Let

   W = savings
   then,

   (2) $P_{wtd} = P_{sc} * \{1 + [(K - 1) * W]\} =$

   For our example, this calculation would be:

   P_{wtd} = 7 * {1 + [(4 – 1) * 77%]} = 23

4. ANALYSIS AND RESULTS

To estimate SmallSat I&T costs, we created two models:

1. A logarithmic model is created using total points of integration as the input; the I&T savings are accounted for in the model selection since a logarithmic model assumes a learning curve.

2. A linear model is created using weighted points of integration as the input; the I&T savings are accounted for in the input data.

The results of the total points and weighted points analyses are seen in Figures 2 (top) and 3 (bottom) respectively. A lognormal curve fits the total points of integration data with an R^2 of 72% while a linear curve fits the weighted points data with an R^2 of 73%. The CERs are as follows with y being

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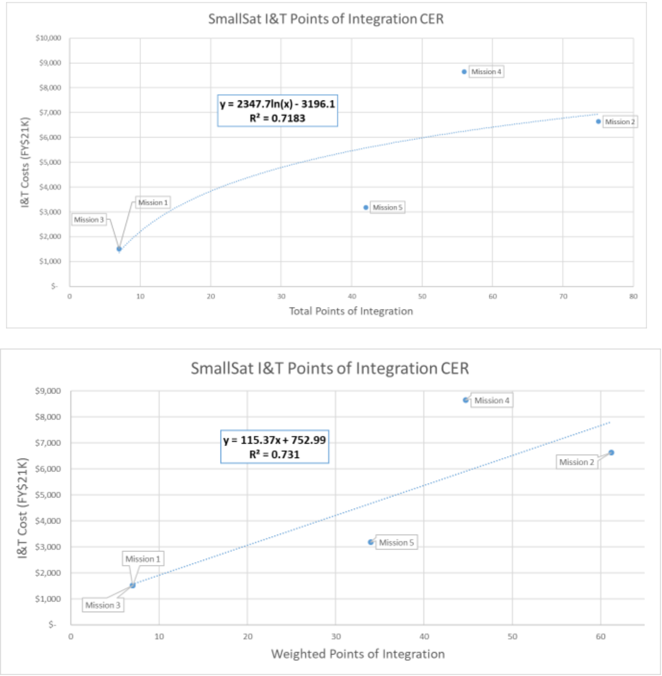
[2] Mabrouk, Elizabeth. *What Are SmallSats AND CUBESATS?* www.nasa.gov/content/what-are-smallsats-and-cubesats.

predicted I&T costs (FY$21K) and x being the points of integration:

1. $y = 2{,}348\ln(x) - 3{,}196$
2. $y = 115x - 753$

Figures 2 & 3. Results



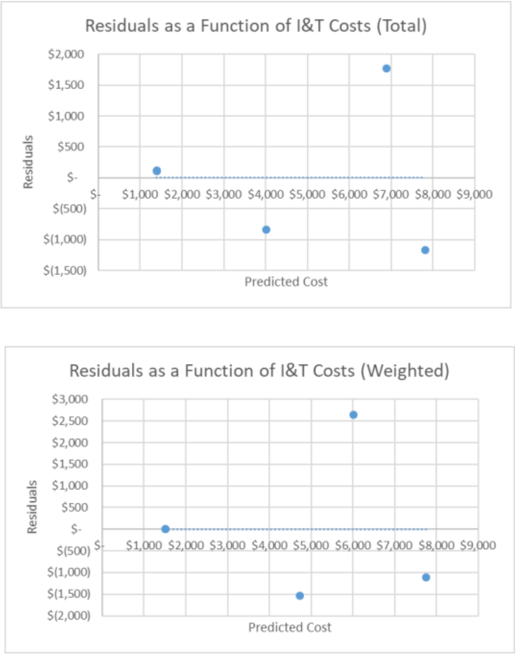
To validate the CER, the points of integration were plugged back into both CERs as the independent variables to produce predicted I&T costs. The predicted costs compared to the actual costs of the full dataset can be seen in Table 3. As shown in Table 3, the prediction errors are 7% and -5%. Since both CERs have low prediction errors, both models are accurately accounting for I&T savings.

Table 3. Predictability

Actuals		Total Points		Weighted Points	
Mission	Cost Actuals (FY$21K)	Predicted Cost	Delta	Predicted Cost	Delta
1	$ 1,511	$ 1,513	0%	$ 1,561	3%
2	$ 6,643	$ 7,755	17%	$ 7,814	18%
3	$ 4,284	$ 1,513	-1%	$ 1,561	3%
4	$ 8,653	$ 6,011	-31%	$ 5,913	-32%
5	$ 3,188	$ 4,726	48%	$ 2,711	-15%
Average			*7%*		*-5%*

Lastly, we tested for heteroscedasticity, unequal variance and scatter, in both models by plotting the residuals against the predicted cost as seen in Figures 4 and 5. The residuals should be homoscedastic, meaning having a constant variance and scatter. Because the trendline has zero slope, the errors are uncorrelated, and thus the model is homoscedastic. This is desirable in order to be able to trust our model results.

Figures 4 & 5. Heteroscedasticity



5. AREAS FOR FURTHER RESEARCH

Some diagnostic tests revealed a distinction between who performed I&T, but there was no statistically significant relationship. We hypothesize that when I&T labor consists largely of university graduate students, I&T costs are low compared to labor performed by professional engineers at NASA centers and especially contractors (due to contracting fees for outsourcing). However, we need more data to confirm or disprove any statistically significant difference.

In addition, we looked at a wrap factor CER that showed a strong relationship for constellations of SmallSats with an R^2 of 97%. This model comprises only three data points; thus, we need more data to see if this relationship holds.

Mass also appears to be a good predictor of total points of integration and I&T costs with an R^2 of 75% and 80%, respectively. Combining the two, mass can be used to predict total points. Then, total points of integration (predicted by mass) can be used to predict I&T costs resulting in another high R^2 of 80%. However, we need more data.

6. CONCLUSION

The goal of this study was to develop a CER for SmallSat I&T costs. The study also highlights areas for future investigation and expansion of the CER. We have reason to estimate I&T costs for small satellites differently than typical missions with larger hardware bases. However, the models that we currently have could be improved. The limited dataset prevents us from finding stronger statistical relationships and identifying statistically significant variables.

In conclusion, the two models that we currently have are legitimate and a step in the right direction. Obtaining more data will allow for model refinement.

BIOGRAPHY

Rachel Sholder *is a parametric cost analyst within the Systems Engineering Group of the APL Space Exploration Sector. She joined APL in 2017 after graduating with an M.S. in statistics and a B.S. in Mathematics from Lehigh University. Rachel has since become a valuable team member responsible for life-cycle space mission cost estimates at various stages of programmatic development (pre-proposal, proposal, mission milestone, trade studies, etc.). She is an active participant in the NASA Cost Estimating Community, maintaining APL's contributions to the NASA Cost Analysis Documents Requirement (CADRe) and the annual NASA Cost and Schedule Symposium. Rachel has advanced knowledge of Excel and is highly proficient with the estimating tools TruePlanning, NICM, and @Risk.*

Kathy Kha *is a parametric cost analyst within the Systems Engineering Group in the Space Exploration Sector at The Johns Hopkins University Applied Physics Laboratory (APL). She joined APL in 2018 after several years in other cost estimating roles. At APL, she is responsible for life-cycle space mission cost estimates at various stages of programmatic development (pre-proposal, proposal, mission milestone, trade studies, etc.). Prior to joining APL, her work included consulting engagements providing cost estimates and proposal evaluation support for NASA source selection panels for space science and Earth science missions, cost estimating support at NASA Ames Research Center, and program office support for an ACAT I Department of Defense acquisition. She has degrees in Applied Mathematics and Systems Engineering and is pursuing a doctorate in engineering at The Johns Hopkins University.*