Aerospace CubeSat Cost Estimating Tool (ACCET)

Shirin Eftekharzadeh, Nichols F. Brown,
Jacob R. Sabol, Manuel E. Puyana,
Angela M. Vu, Amy P. Macrina
The Aerospace Corporation

2022 NASA Cost and Schedule Symposium
April 26-28, 2022

Approved for public release. OTR 2022 -00603.

Introduction

Aerospace CubeSat Cost Estimating Tool (ACCET)

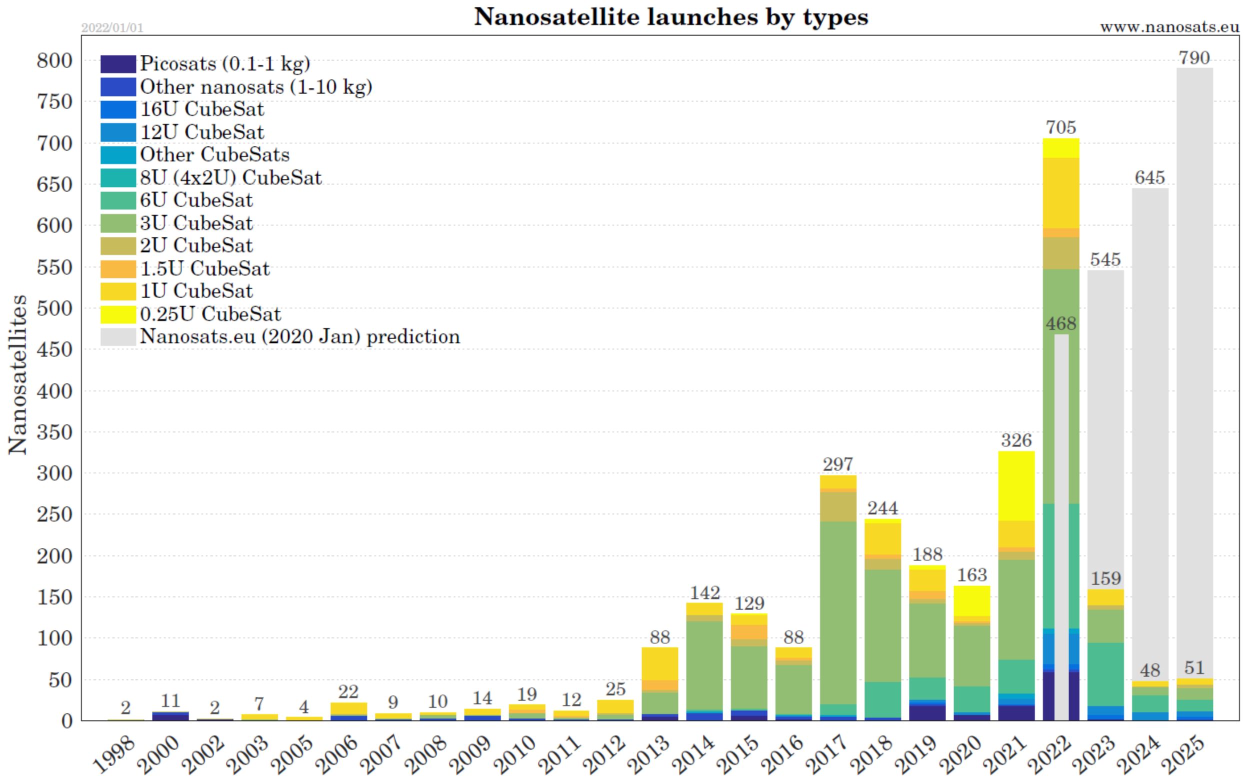
- Over the past decade there has been increasing trend in the use of CubeSats
- However, costing them is a continuing challenge particularly for early design
  - *Collecting credible CubeSat data has been challenging*
  - *Bottoms-Up estimates are time consuming and lack information on uncertainty*
- Desire for simple parametric Cost Estimating Relationships (CERs) to
  - *Enable quick, consistent estimates using objective inputs*
  - *Know uncertainty from the goodness-of-fit based on historical data*
- However, CERs have proven elusive
  - *Prior efforts by Aerospace and in industry have found poor fits to historical data*

ACCET is a new CubeSat parametric cost model developed by The Aerospace Corporation

CubeSat Use is Growing

Overview

- The use of CubeSats have been growing at significant rates
  - *Nanosats Database (nanosats.eu) counts as of January 1, 2022*
    - Nanosats launched: 1663 have been launched since 1998
    - Forecast: over 2500 nanosats to launch in 6 years



CubeSat use is significant and growing, we need better tools to cost them

CubeSat Cost Estimating

State-of-the-Art

- CubeSats are currently costed via
  - *Bottoms-Up approach*
    - Labor intensive to perform each estimate
    - Maintenance requires frequent updates for component level cost and technical data
    - Requires a level of design maturity often not available early in conceptual design
    - Usually, a point estimate without uncertainty range
  - *Analogy-based, non-parametric regression techniques*
    - Can also be applied in early conceptual design
    - Challenging to determine appropriate analogies

- Existing Costs Estimating Relationships (CERs) models are for larger missions, and not applicable to CubeSats
  - *Large: NASA / Air Force Cost Model (NAFCOM) – mass: > 1000 kg*
  - *Small: Small Satellite Cost Model (SSCM) – mass: 100 – 1000 kg*
  - *Micro: Microsatellite Cost Model (MSCM) – mass: 10 – 100 kg*

- Prior efforts by Aerospace and in industry have found poor fits to historical data

ACCET is a successful attempt to create CubeSat CERs

ACCET CubeSat CERs

ACCET has filled the missing piece!

- The Aerospace CubeSat Cost Estimating Tool (ACCET) is a parametric model developed by The Aerospace Corporation to predict the development cost of CubeSats
  - *ACCET is based on an integration of all available CubeSat resources from Aerospace Corporation and other domains to estimate the cost of CubeSat missions*
  - *CERs are derived upon historical actuals and technical data from CubeSat missions*
  - *CERs are based on simple objective independent variables that are readily available early in the design*

- ACCET provides objectivity, ease of use, ease of maintenance, and viable level of accuracy

ACCET

How did we do it?

- Three key factors that helped in developing CERs were:
  - *Increase in the number available CubeSat missions*
    - Collected data on 49 missions
      - *Internal proprietary and open-source data*
      - *Credible cost data was available for 37 of the missions*
      - *18 objective and technical parameters, available early in a mission's maturity*
        - Examination of 100+ combinations of the parameters
  - *Proper cost normalization across CubeSats*
    - *Used First Unit (FU) Development cost of a CubeSat mission rather than the development cost of the entire mission*
  - *Separation of CERs based on each mission's objectives*
    - Splitting Operational / Science vs. Tech Demos

ACCET Database

37 CubeSat Missions

- Collected historical cost and technical data for 49 CubeSat missions launched since 2003
  - *Credible cost data was available for 37 of the missions*
- Mission data was collected from mission documents, mission websites, NASA and internal databases, and articles about the missions
  - *Utilized expert search combined with Aerospace's capability "WebMiner*" to systematically search for publicly available CubeSat cost and technical data*

Credible Cost Data Found			
AeroCube-10	CP8	GRIFEX	QuakeSat
AeroCube-11	CSSWE	Halosat	RACE
AeroCube-12	CSUNSat-1	ISARA	RainCube
AeroCube-14	CINEMA	MarCO	RAX 1 & 2
AeroCube-15	DICE 1 & 2	MiRaTa	SporeSat-1
AeroCube-3	EDSN	M-Cubed / COVE	Tempest-D
AeroCube-4A	FIREBIRD-A	NEAScout	Sensitive Data 1
AeroCube-5A	Firefly	O/OREOS	Sensitive Data 2
AeroCube-7	Genesat-1	PharmaSat 1	Sensitive Data 3
ASTERIA			

No Credible Cost Data Found	
Armadillo	PSSC-2
BeVo-2 Cube	SkyCube
Ho'oponopono-2	SMDC-ONE
Perseus	SNaP
Prometheus	NanoSail-D2
CPOD	LMRST

*Natural language processing tool trained on Aerospace internal documents

ACCET CER Parameters

100+ combinations of 18 cost and technical parameters attempted

Variable Type	Parameter Name	Unit	Definition
Dependent Variables	**Total Mission Cost**	$	Total development & operations cost of the CubeSat mission (Phase A-E)
	Space Development Cost	$	Total development cost of the CubeSat space segment (Phase A-D)
	Space Dev Cost / kg	$ / kg	Total space segment development cost per single CubeSat mass
	Space Dev Cost / U	$ / U	Total space segment development cost per CubeSat U's
	First Unit Cost	$	CubeSat Space Development Cost (Phase A-D) for first unit produced
	First Unit Cost / U	$ / U	Total First Unit development cost per CubeSat U's
Independent Variables	**University Built?**		Is the CubeSat primarily developed in a university setting using student labor?
	CubeSats in Constellation	#	Total number of CubeSats in a constellation
	Total Constellation Mass	kg	Total mass of all CubeSats in a constellation
	CubeSat Mass	kg	Total mass of a single CubeSat in a constellation
	Total Constellation U's	#	Total number of U's for all CubeSats in a constellation
	CubeSat U's	#	Total number of U's for a single CubeSat in a constellation
	Operational/Science vs. Tech Demo Mission		Mission primarily intended for operational or scientific applications vs. a mission primarily intended to demonstrate new technologies
	Design Life	months	CubeSat design life requirement (If unspecified, use minimum duration needed for mission to demonstrate or fulfill primary goals)
	Number of Instruments	#	For Operational/Science, total number of instruments on a single CubeSat
	Number of Tech Demo Payloads	#	ForNumber of instruments which the CubeSat missions considers as tech demonstrations
	Tech Demo of a Payload vs. Bus Instrument		For a Tech Demo, is the primary mission demonstrating a new bus or payload technology?
	Development Time	months	Amount of time to develop a CubeSat mission in months (ATP - Delivery)

Mission Normalization and Classification

Normalizing to Cost per First Unit Equivalent

- ACCET normalizes a mission's cost to a First Unit Equivalent Cost
  - *Most CubeSat projects only provide Total Mission Cost*
    - However, this "total" could include multiple builds in a constellation
    - The cost to build multiple unit is expected to exceed that of a single unit
  - *Assumed cost of each additional unit in a constellation is 1/3 the cost of the first unit (Non-Recurring + Recurring)*
    - Rule-of-thumb based on work with small satellite SC busses, microsats, and instruments
    - Did not assume learning for additional units
    - It is very rare for projects to provide cost by unit; however, the single data point available was consistent with the 1/3 cost assumption for additional units

- Other normalization approaches were considered that did not work
  - *Total Mission Cost, Space Development Cost, Space Dev Cost / kg, Space Dev Cost / U, First Unit Cost / U*

- Normalization of Total Space Segment cost to First Unit Equivalent was the only approach that led to viable correlations

Mission Normalization and Classification

Operational / Science vs. Tech Demo Classification

- ACCET uses two separate CERs based on a CubeSat's mission objective
  - *Operational / Science: Main mission objective is primarily intended for operational or scientific application, not demonstrating a new technology*
  - *Technology Demonstration: Mission classified itself as a tech demo and/or the main mission objective is to demonstrate a new technology*

- Separate CERs were pursued rather than a single all-encompassing CER as some subsets of missions correlated drastically better than the whole database

- Other classifications were explored to generate separate CERs, but did not produce viable results
  - *CubeSat Mass Ranges*
  - *CubeSat U Ranges*
  - *University Built*
  - *Instrument Type*

- Operational / Science vs. Tech Demo CubeSat separation led to the most viable CERs

Regression & Validation Method

How did we iterate & validate the CERs?

- General Error Regression Model (GERM)
  - *Multiplicative error typically preferred for cost estimation*
  - *Minimizes the sum of squared percentage errors*
  - *Also used for Aerospace's Small Satellite Cost Model (SSCM) and Mission Operations Cost Estimation Tool (MOCET)*

- Leave One Out Cross Validation (LOOCV)
  - *Helps determine the best candidate estimating relationship among several possible candidates*
  - *Computes the total error of each test example to help determine the best candidate estimating relationship*

- Additional details available in the back-up

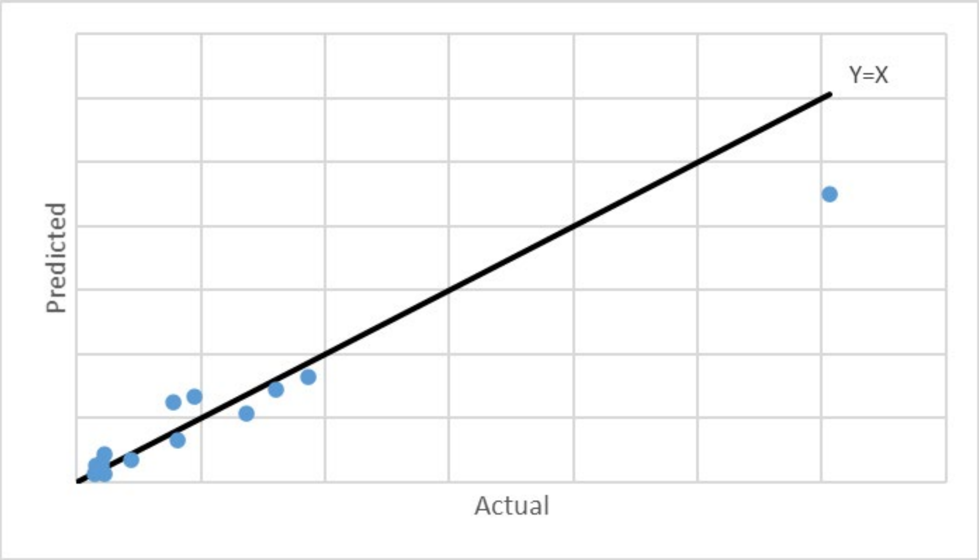
Operational / Science CubeSat CER

- CER Output

Output	Units	Definition
First Unit Cost	FY21 $K	CubeSat Space Development Cost (Phase A-D) for first unit produced

- Goodness of Fit

Measure	Value
Regression Method	GERM ZMPE
Standard Error of the Estimate	35.89%
Average Percentage Bias	0.00%
Pearson's Correlation Sqd (r^2)	0.956
Number of Observations	14
Number of Input Variables	2



- Database

Missions	
CINEMA	NEAScout
CSSWE	O/OREOS
DICE 1 & 2	PharmaSat 1
FIREBIRD-A	QuakeSat
Firefly	RAX 1 & 2
Genesat-1	SporeSat-1
Halosat	Sensitive Data 3

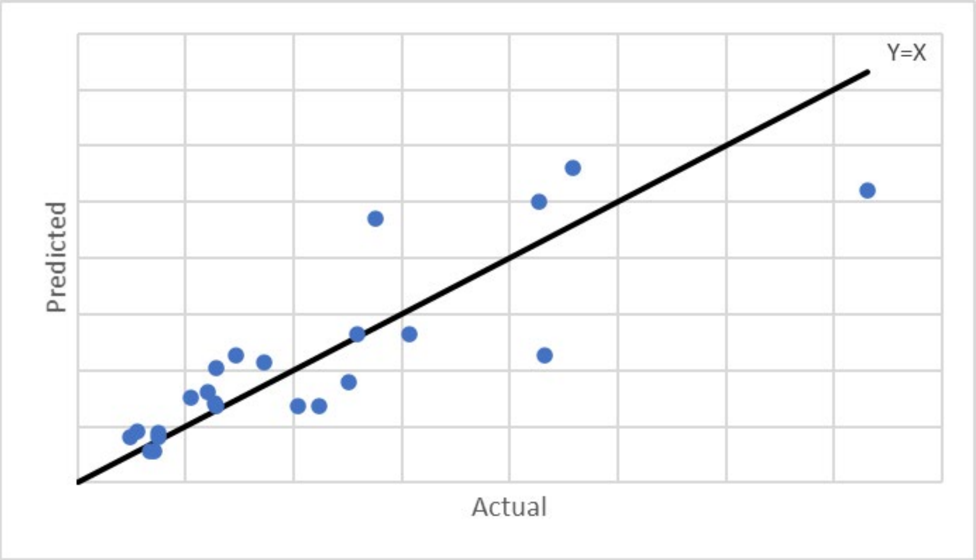
Tech Demo CubeSat CER

- CER Output

Output	Units	Definition
First Unit Cost	FY21 $K	CubeSat Space Development Cost (Phase A-D) for first unit produced

- Goodness of Fit

Measure	Value
Regression Method	GERM ZMPE
Standard Error of the Estimate	37.84%
Average Percentage Bias	0.00%
Pearson's Correlation Sqd (r^2)	0.713
Number of Observations	23
Number of Input Variables	2



- Database

Missions	
AeroCube-10	EDSN
AeroCube-11	GRIFFEX
AeroCube-12	ISARA
AeroCube-14	MarCO
AeroCube-15	M-Cubed / COVE
AeroCube-3	MiRaTa
AeroCube-4A	RACE
AeroCube-5A	RainCube
AeroCube-7	Tempest-D
ASTERIA	Sensitive Data 1
CP8	Sensitive Data 2
CSUNSat-1	

ACCET

Conclusion

- CubeSats are a growing trend, but parametric cost models were unavailable

- ACCET is a new CubeSat parametric cost model developed by The Aerospace Corporation
  - *Estimates the First Unit Development Cost*
  - *Fills missing gap*
  - *Composed of objective technical parameters typically available early in development*

- Key factors leading to the success of ACCET
  - *Expanding database consisting of 37 CubeSat missions*
  - *Normalizing CubeSats to the First Unit Development Cost*
  - *Segregating Operational / Science vs. Tech Demos missions*

- ACCET provides objectivity, ease of use, ease of maintenance, and viable level of accuracy

Backup Slides

Contact Information

Conclusion

- Dr. Shirin Eftekharzadeh
  - *shirin.eftekharzadeh@aero.org*
- Nichols F. Brown
  - *nichols.f.brown@aero.org*
- Jacob R. Sabol
  - *jacob.sabol@aero.org*
- Manuel E. Puyana
  - *manuel.e.puyana@aero.org*
- Angela M. Vu
  - *angela.vu@aero.org*
- Dr. Amy P. Macrina
  - *amy.p.macrina@aero.org*

Regression Methodology (1 of 2)

- General Error Regression Model (GERM)*
  - *Multiplicative error typically preferred for cost estimation*
  - *Minimum Percentage Error (MPE) / Zero Percentage Bias (ZPB)***
  - *Minimize the sum of squared percentage errors:*

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

y_i actual
$f(x_i)$ estimate

Average percentage bias (APB) of estimate constrained to zero

$$APB = 100\% * \frac{1}{n}\sum_{i=1}^{n}\frac{(f(x_i) - y_i)}{f(x_i)}$$

- Measures of goodness of fit

Standard percentage Error of the Estimate (SEE)

$$SEE = 100\% * \sqrt{\frac{1}{n-m}\sum_{i=1}^{n}\left[\frac{y_i - f(x_i)}{f(x_i)}\right]^2}$$

n number of observations
m number of input variables

Pearson product moment correlation squared (r^2)
(Excel RSQ formula)

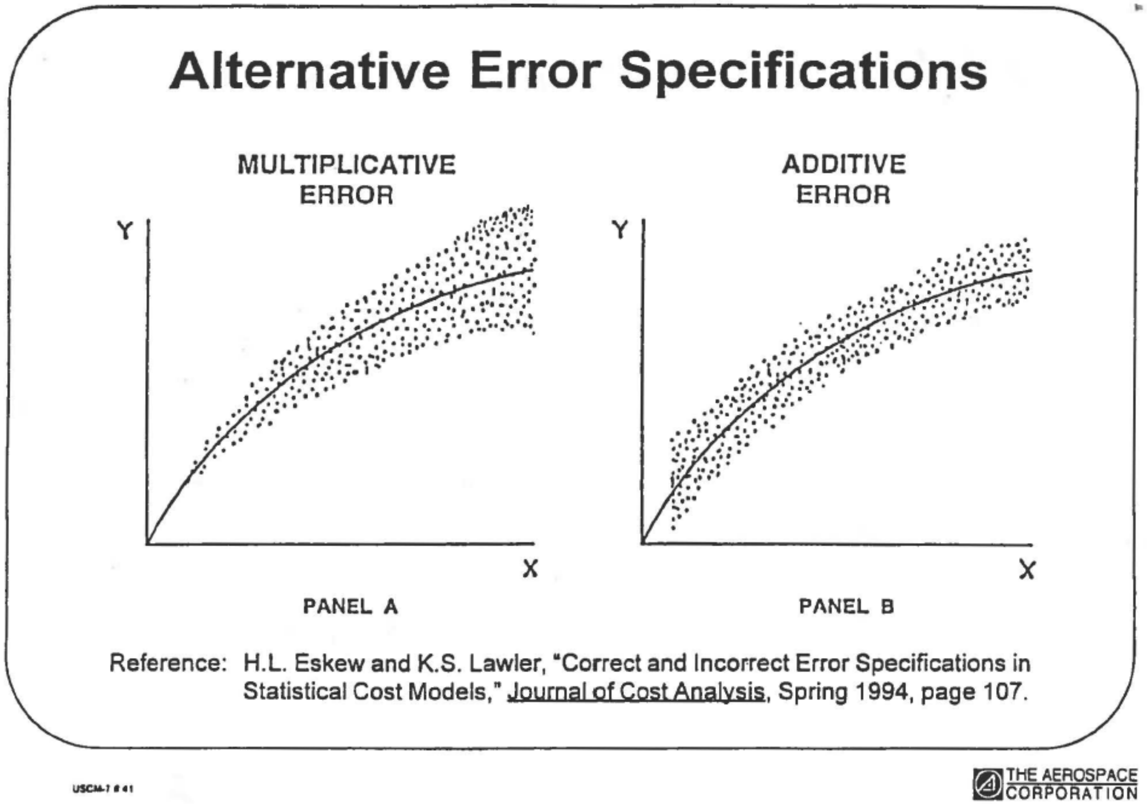
$$r = \frac{\sum_{i=1}^{n}(y_i - \bar{y})(f_i - \bar{f})}{\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2 * \sum_{i=1}^{n}(f_i - \bar{f})^2}}$$

$\bar{y}$ average of actuals
$\bar{f}$ average of estimates

*General-Error Regression for USCM-7 CER Development, S. A. Book and P. H. Young, 28th Annual DoD Cost Analysis Symposium, 21 September 1994
**Deriving Minimum-Percentage-Error CERs Under Zero-Bias Constraints, S. A. Book and N. Y. Lao, 64th Military Operations Research Society, 18 June 1996

Regression Methodology (2 of 2)

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



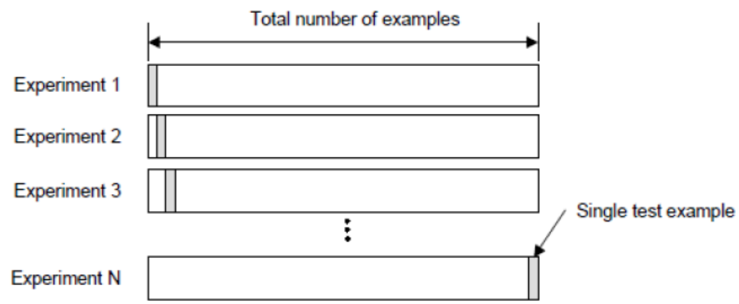
$$\sum_{i=1}^{n}\left[y_i - f(x_i)\right]^2$$

- Multiplicative error is generally applicable for cost estimation
  - *Penalizes more heavily for incorrect estimates on the low end*
- Additive error more applicable for models where there is constant variance
- Data should be analyzed to determine which type of error fits the problem at hand

General-Error Regression for USCM-7 CER Development, S. A. Book and P. H. Young, 28th Annual DoD Cost Analysis Symposium, 21 September 1994

Validation Methods

- Leave One Out Cross Validation (LOOCV) helps determine the best candidate estimating relationship among several possible candidates
  - *LOOCV method for a dataset with N examples, performs N experiments*
  - *Each experiment use N-1 examples for training and the remaining example for testing*



- Computes the total error of each test example to help determine the best candidate estimating relationship

- Will use additional CubeSat cost data to aid in future validation