The EZ Phase E Model

Andy Prince
a.prince@newhorizon5.com
256-583-0236
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Background

- **Early 1990's: NASA cost estimators had no tools for estimating Phase E cost**
- **Mid-1990's: Dave Pine commissioned a mission operations cost model development team lead by Del Wilson**
  - Mark Jacobs and Andy Prince were members
- **With significant help John Carraway at JPL and inputs from GSFC, Mark developed the Space Operations Cost Model (SOCM)**
- **In 2015 the Aerospace Corporation released the first version of the Mission Operations Cost Estimating Tool (MOCET)**
  - Sponsored by SOMA
- **Also, in 2014 the PCEC v1.1 was released with a simplified version of SOCM and the ability to link to a full SOCM (and later MOCET) estimate**

Yet Phase E Cost Growth Continues to Vex

- **Phase E is a low priority early in the project life cycle**
- **Phase E is difficult for estimators to conceptualize**
- **Phase E cost growth continues apace**
  - 2014 Aerospace study of 6 missions: range of 4% to 151% Phase E cost growth since KDP-C with an average of 57%
  - 2023 APL study of 3 New Frontiers missions: average of 51% in Phase E cost growth
- **October 2023: SMD chartered "Phase E Cost Study Independent Study Team"**

> "It has become increasingly common for Science Mission Directorate (SMD) missions to under-budget Phase E. It has also become increasingly common that such issues are not brought to SMD leadership's attention until as late as Key Decision Point E (KDP-E) in the project lifecycle. Both project estimates and independent assessments are inadequate to the task. It is recognized that Phase E plans are not definitized until late in the project lifecycle, often after mission Critical Design Review (CDR) or even in Phase D, adding to the challenge in improving the situation. Nevertheless, SMD is expected to set the correct Agency Baseline Cost (ABC) at KDP-C."

It was an Accident

- Doing research into Phase E cost for planetary missions for upcoming Europa Clipper ORR *and* doing some research into CER development using my new (old) complexity factor approach
- Data for the research is from the PCEC CER data set that had somehow magically appeared on my computer
- Found that Phase A–D cost was highly predictive of Phase E/F cost
- Began looking for other parameters that might be correlated with Phase E/F cost
- Developed and tested candidate CERs, selected best candidate for further study

R^2 and $MUPE^2$ Used to Evaluate CERs

- For the Power Equation with Multiplicative Residuals, i.e.,

$$Y = aX^b\varepsilon$$

- The Regression Estimates Vary Based on the Variation of the Residual

$$\varepsilon = \frac{Y}{aX^b}$$

- Also Common to Adjust This to Treat ε as a Percentage, i.e., Set

$$Y = aX^b(1+\varepsilon)$$

$$\varepsilon = \frac{aX^b - Y}{aX^b} = \left[\frac{Estimate - Actual}{Estimate}\right]^2$$

- Actual Cost = Estimate +/- Percentage of Estimate

CER Equation Form, Derived thru LTOLS

Evaluated other variable transforms without success

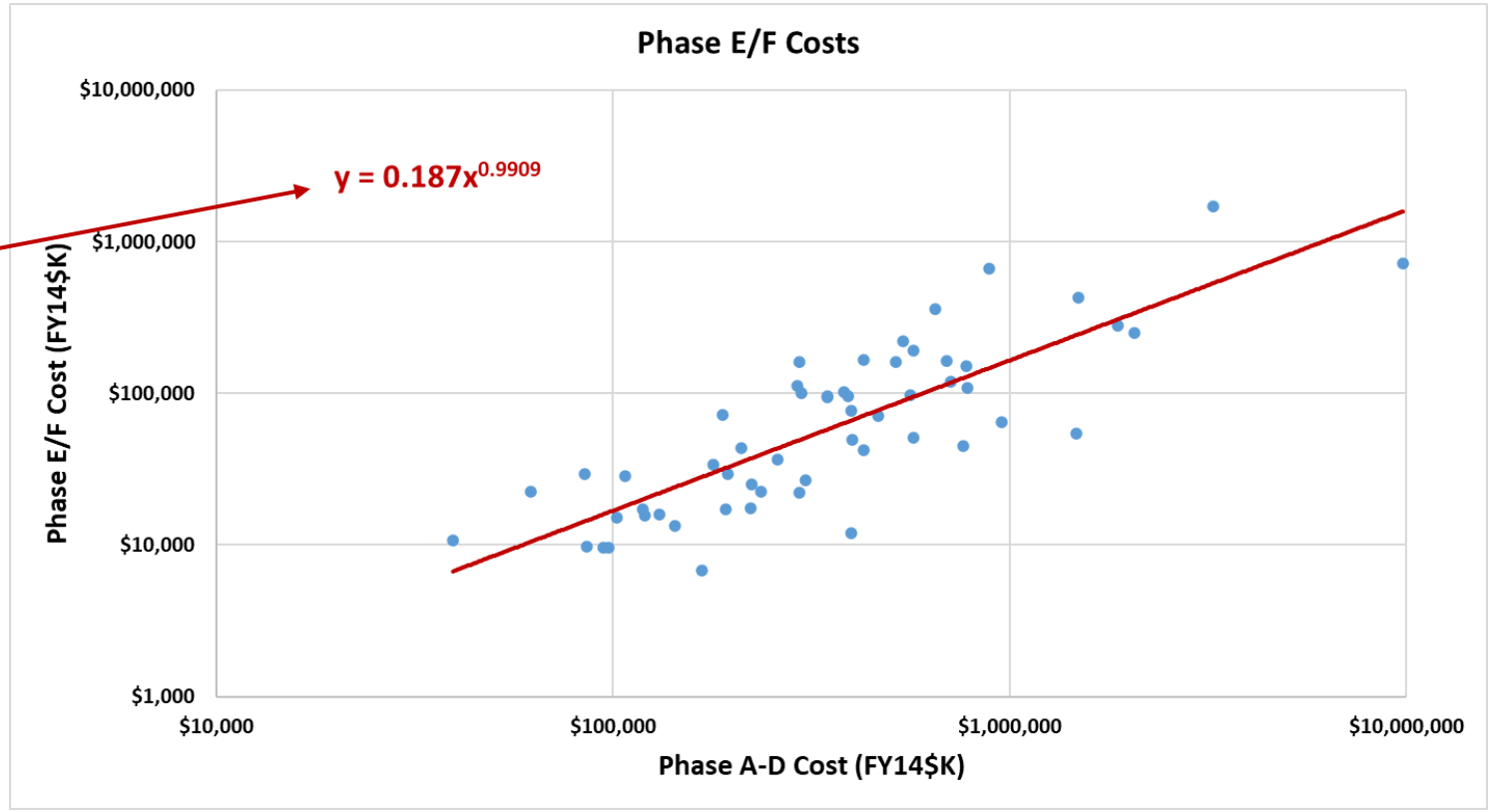
Goodness of Fit Calculated using the Minimum Unbiased Percentage Error (MUPE) Ratio, Squared for Each Data Point

Stolen from Christian Smart's paper "Cutting the Gordian Knot: Maximum Likelihood Estimation for Untransformed Lognormal Error

Are Cost-to-Cost CERs Valid?

- **Yes!**
  - Logical in many (most?) situations
  - Functions like mass for subsystem CERs
  - Statistically valid
- **No!**
  - Cost not based on system characteristics **(?)**
  - Bad input cost estimate = bad output cost estimate
  - Simple percentage factors may not scale

Note that Phase E/F cost is equal to 19% of the Phase A-D cost *on average*



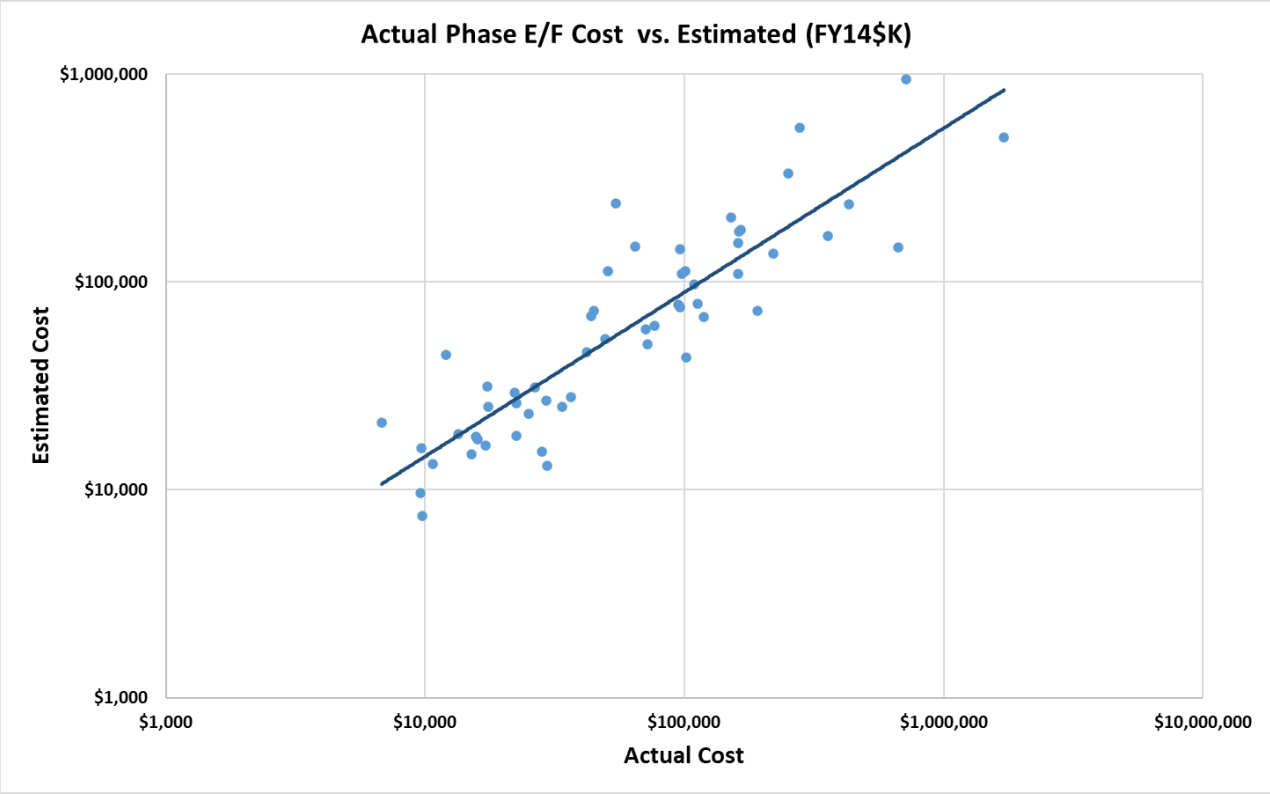
The Model

$$\text{Phase E/F Cost (FY14\$K)} = 1.031(\Phi \text{ A-D \$})^{0.679}(\text{Months})^{0.547}(\#\text{FltSys})^{0.260}(\text{EOFlag})^{0.560}$$

Input Variables

- **Phase A-D Cost** in FY14$K without Launch Vehicle but including UFE
- Total Phase E/F **Duration** in Months
- **Number of Flight Systems**: Either Number of Identical Spacecraft or Number of Distinct Flight Elements (i.e., Mars Mission Cruise Stage, EDL System, and Lander)
- **Earth Orbit Flag**: 1 for Earth Orbit; e for Beyond Earth Orbit

Plots and Statistics



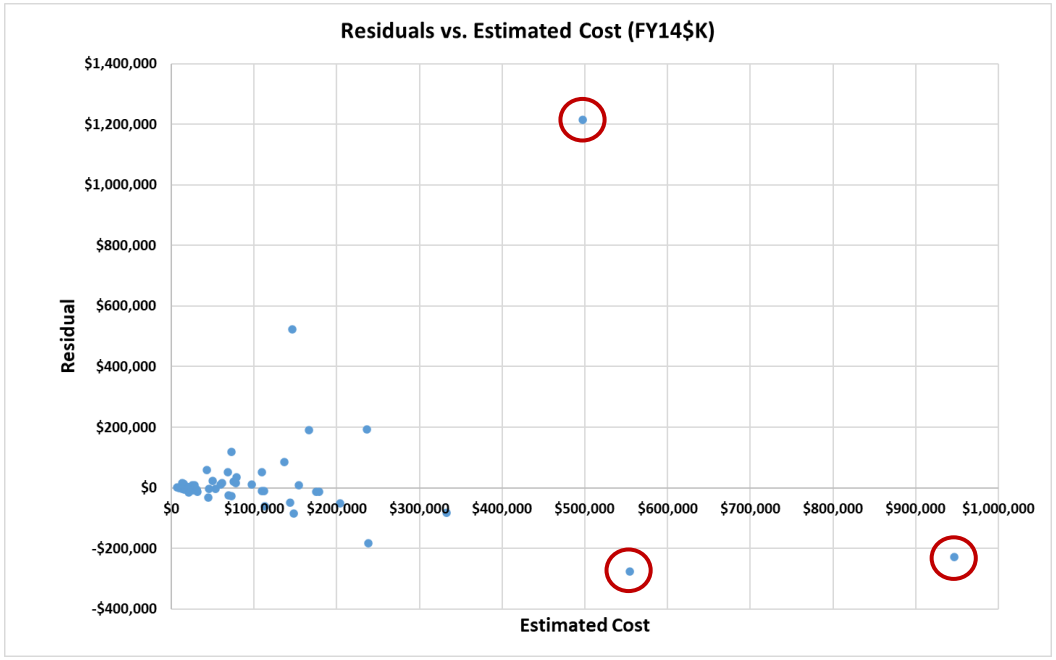
Regression Statistics	
Multiple R	0.889
R Square	**0.790**
Adjusted R Square	0.773
MUPE Square	**0.597**
Standard Error	0.591
Observations	56

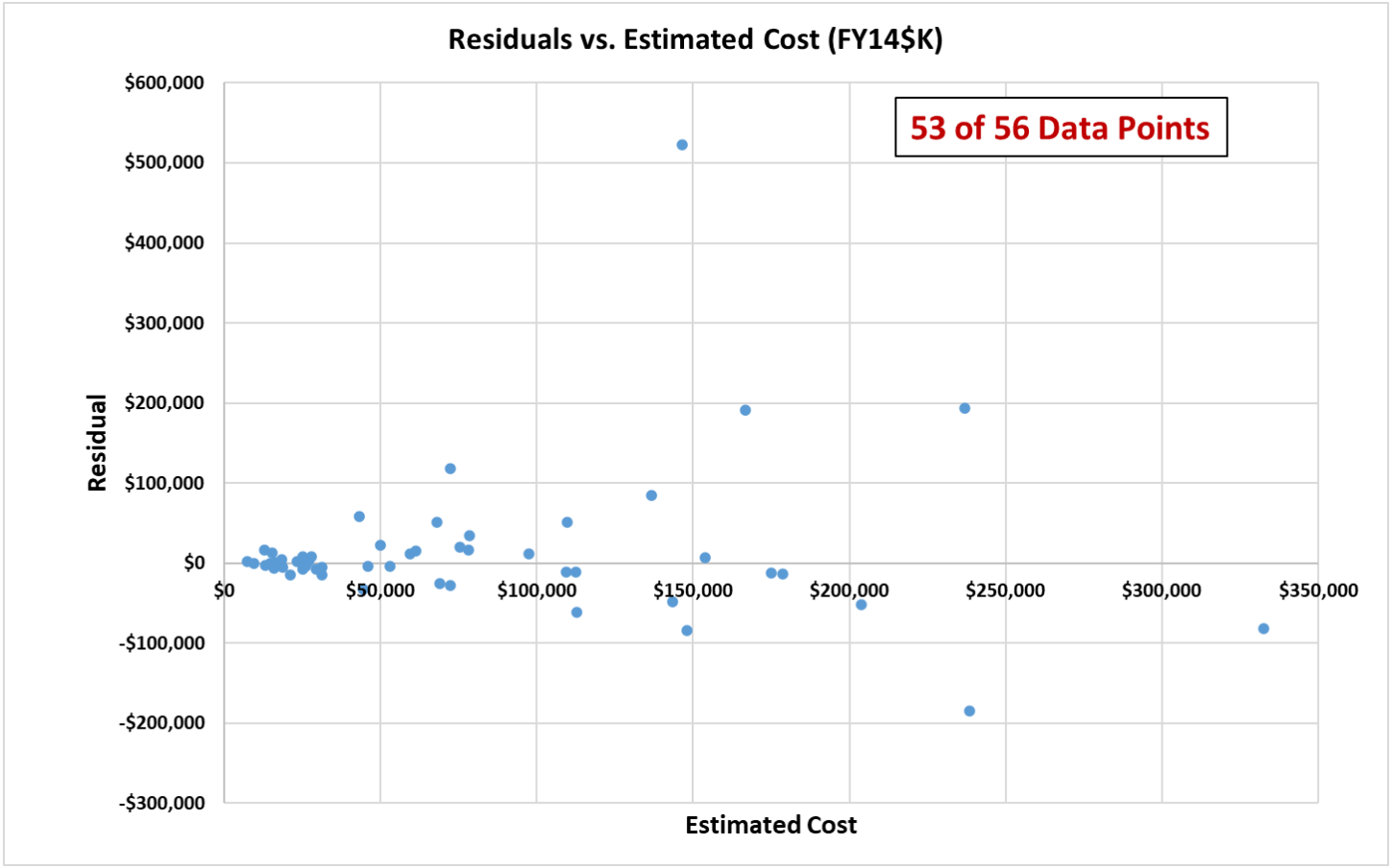
ANOVA

	df	*SS*	*MS*	*F*	*Significance*
Regression	4	66.978	16.745	47.888	0.000
Residual	51	17.833	0.350		
Total	55	84.811			

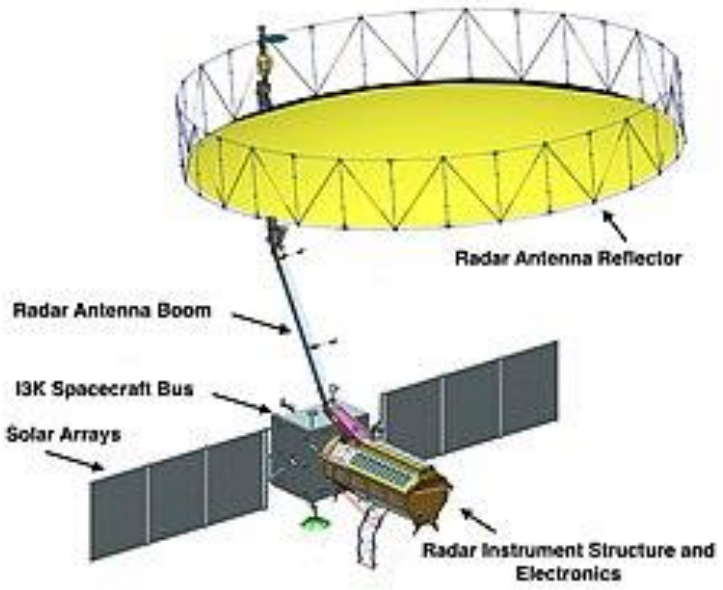
	Coefficients	***Std Error***	***t Stat***	***P-value***	***Lower 95%***	***Upper 95%***
Intercept	0.031	1.050	0.029	0.977	-2.077	2.139
Phase A-D	0.679	0.097	7.015	0.000	0.485	0.873
Duration	0.547	0.113	4.829	0.000	0.319	0.774
# Flt Sys	0.260	0.155	1.679	0.099	-0.051	0.570
EO Flag	0.560	0.169	3.303	0.002	0.219	0.900

Residual Plots





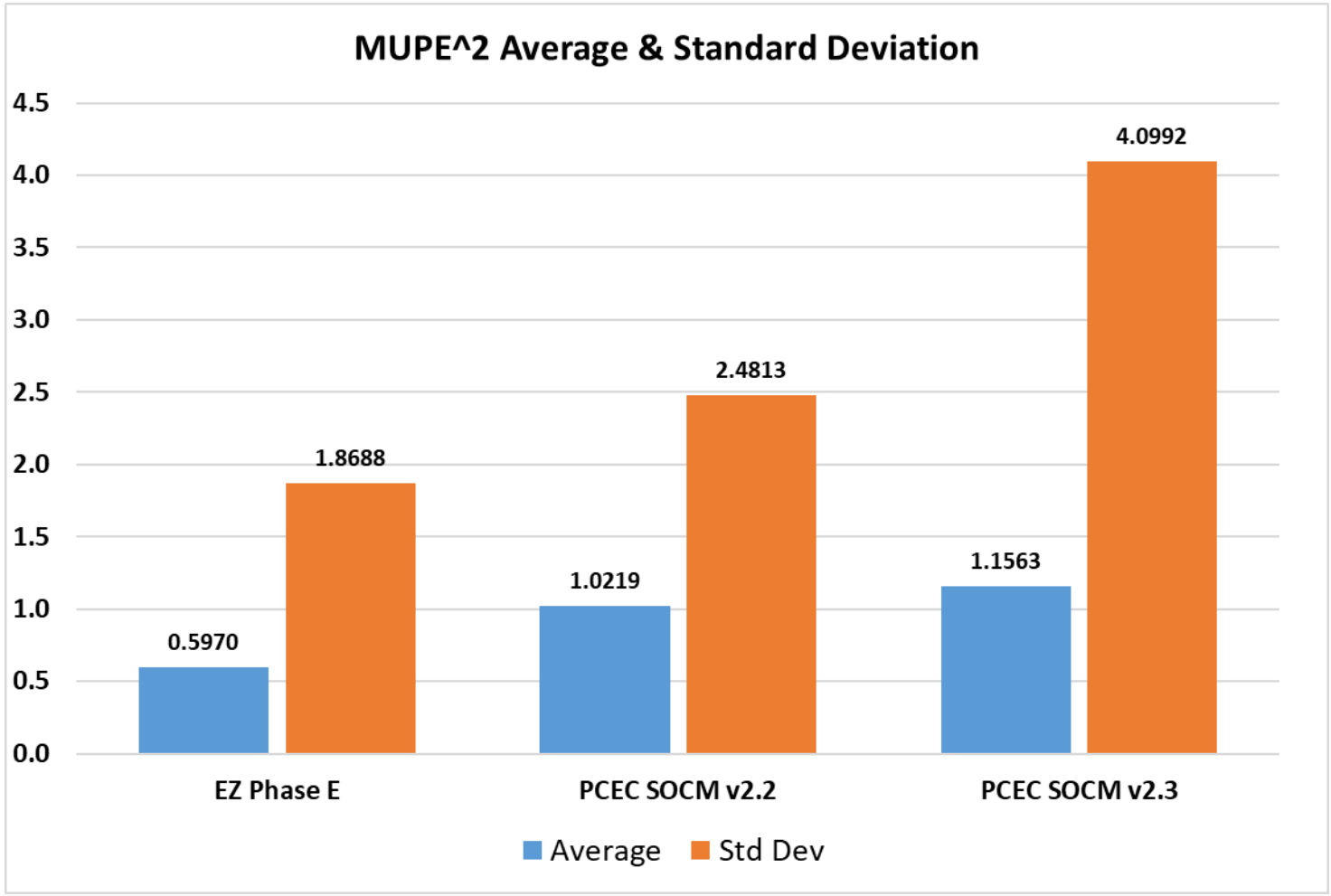
Testing the Model



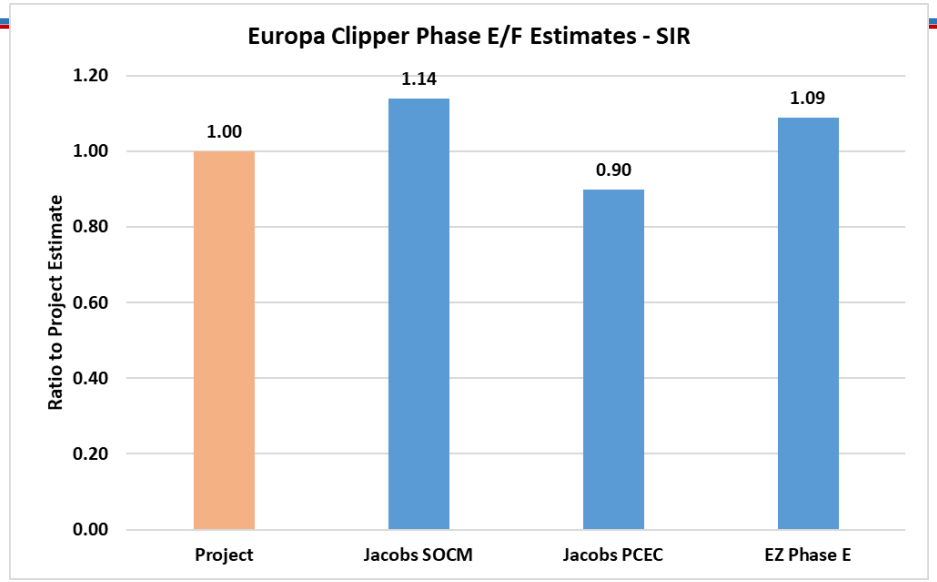
- **Compare to PCEC SOCM v2.2 and v2.3**
- **Real world testing using one proposed and two missions in development**
  - Europa Clipper
    - Flagship mission to the Jovian Moon Europa, managed by JPL
  - NISAR (pictured to left)
    - Joint radar mapping mission between NASA and the Indian Space Agency, managed by JPL
  - MoonBEAM
    - Small satellite mission in Lagrange orbit to observe and report high energy transient events (i.e.; gamma-ray bursts) in near real time, proposed by MSFC

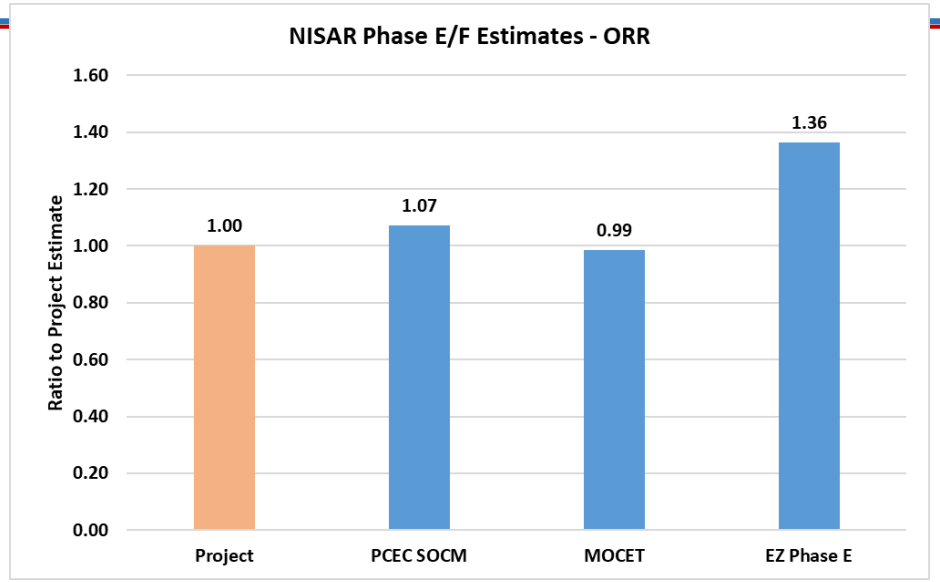
Comparison to PCEC SOCM

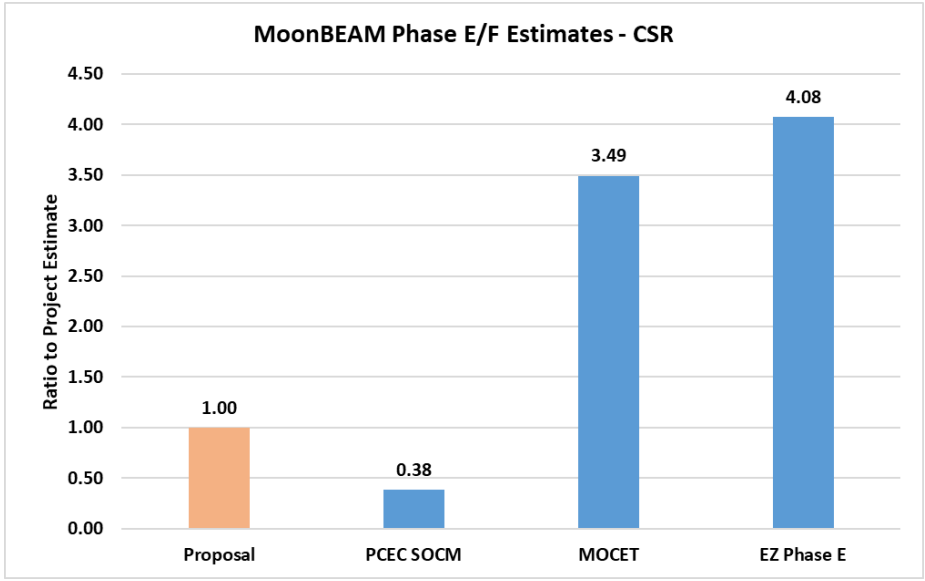
- **Used PCEC SOCM v2.2 and 2.3 to estimate the Phase E/F cost for 54 of the 56 missions used to develop the EZ Phase E model**
  - Insufficient data for GOES (-P) and JPSS-1
- **Calculated the MUPE^2 averages and standard deviations**
- **Differences between v2.2 and v2.3**
  - v2.2 has two CERs: Near Earth and Planetary
    - Near Earth uses SOCM Level 1 Score and Daily Download Volume in GB
    - Planetary uses Daily Download Volume and Number of Observing Modes
  - v2.3 has one CER that uses Flight System Mass (in KG), SOCM Level 1 Score, and Peak Download Rate in MB



Real World Testing

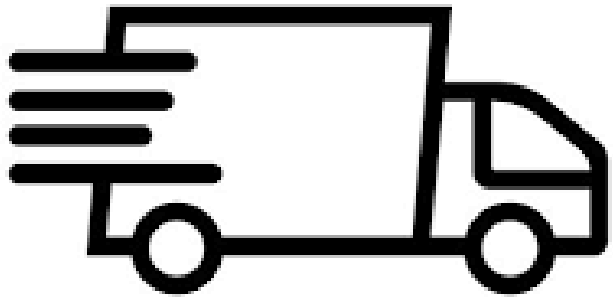






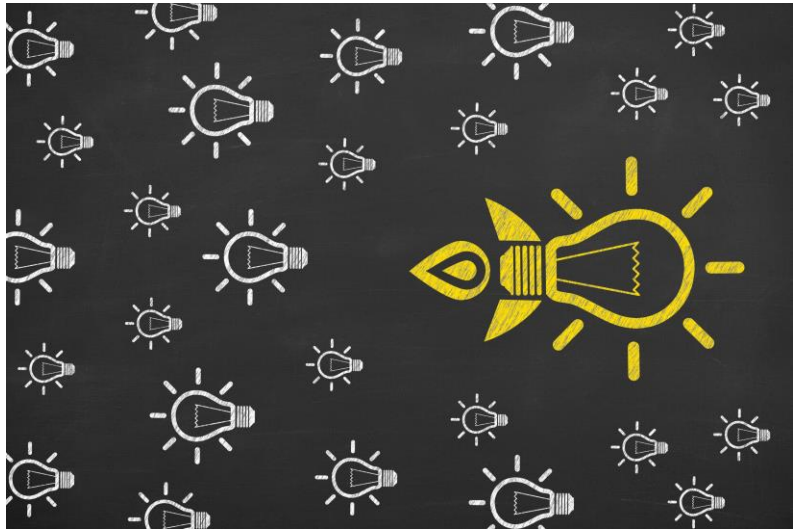
Takeaways

- **Statistically, EZ Phase E Model is equal to or better than PCEC SOCM**
- **Easier to use than SOCM or MOCET (Quickcost class model?)**
- **Real world applications show mixed results, but no model is demonstratively superior**



Future Work

- **Perform Cross-Validation to test coefficients**
- **Investigate adjustment and complexity factors**



"All you need in this life is ignorance and confidence; then success is sure."

Mark Twain

Sources

- McNeill, Justin; “An Examination of the Leading Indicators of Phase E Cost and Staffing Growth and Methods for Their Use,” The Aerospace Corporation, August 12, 2014
- Kha, Kathy; Clare, Ben; “You Get What You Pay For: The New Frontiers 5 Operations Cost Cap,” Johns Hopkins Applied Physics Laboratory, 2023 NASA Cost and Schedule Symposium