Cost Model Validation: A Technical and Cultural Approach

Jairus Hihn Leigh Rosenberg' Kevin Roust Keith Warfield

Jet Propulsion Laboratory'
4800 *Oak* Grove Drive
Pasadena, CA 91109

Abstract. This paper summarizes how JPL's Parametric Mission Cost Model (PMCM) has been validated using **both** formal statistical methods and a variety of peer and management reviews in order to establish organizational acceptance of the cost model estimates. The need for statistical and also organizational validation is heightened when providing cost models and cost estimates in a concurrent engineering environment typical of the advanced design teams that exist **at** ***JPL*** as well **as** at other aerospace organizations, e.g. Aerospace Corporation and Goddard Space Flight Center.

Topics discussed include

1. Statistical Validation Approach and Results
2. Organizational Validation (review) process and **how** it developed support **and** consensus for the model at **an** engineering and project management level
3. Discussion of **how** validation drove the shape and content of the model.

INTRODUCTION

The Jet Propulsion Laboratory (JPL) in Pasadena, California is a **US** Government Federally-Funded Research and Development Center, which is run by the California Institute of Technology for the National Aeronautics and Space Administration **(NASA).** JPL's primary role is to build and operate unmanned, robotic space exploration missions throughout **our solar** system. From the period of the mid-1960's until 1992, there were **16** missions over the 29-year period. This number of completed missions required that about 5 to 10 proposals a year were produced. Since **1992,** there has **been** a dramatic increase in the number **of** missions launched each year, there were six launches in 1998-99 alone. Instead of generating 5 to **10** proposals per year, JPL now produces **50** to 80. In addition these new missions are constantly changing their development processes **as** they evolve attempts at implementing "Faster, Better, Cheaper" **(FBC).** Factors that have made these recent missions more cost efficient are: increased inheritance fiom previous missions, reduced redundancy (increased risk), simplified documentation and reviews, **and** more work done in parallel during the development cycle. In the rush to implement **FBC,** it is now generally recognized that NASA and JPL have pushed the paradigm too far. However, today's missions are still designed, built, and operated differently than they were **20** years **ago.**

In 1995, **as** a way to deal with **the** large number of proposals being generated, **JPL** formed **an** Advanced Projects Design Team (APDT), called Team X. One of the first issues that arose

[1] **The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.**

related to the need for cost estimation models and processes that would work in a concurrent engineering environment and would provide 'reliable' cost estimates for **JPL's** new missions. Secondly, with **so** many proposals there were times when a cost model was required that could be used without convening the entire 15-member Team X.

A major problem was that useful historic data on which such models are typically constructed did not exist, since this new way of doing business **was** different than that of the past. Even the missions starting in **1992,** which were FBC, had not all yet flown.

For the subsystem cost models, the solution implemented was to use Mars Pathfinder **data** to parameterize their quasi–bottom up cost estimation process. The mission level parametric model presented a more difficult problem **as** a complete data set on a significant number of missions was required to be able to derive regression based Cost Estimating Relationships, CERs. For what **was** to become JPL's PMCM the decision **was** made to **use** the results of previous Team X studies to derive the CERs. **This** meant that the CERs were a parametric model that reproduced the expert judgment contained within Team X. Of course, this raised a very critical **question: Why** should anyone trust a model not based on actual historical **data?**

Actually, this question is **a** mandatory question for all CER's. Addressing this question is especially important in an organizational context where project managers **and** non-cost experts must sign **off** on a proposal. The fundamental answer is that the model must be validated both statistically and organizationally **and** the results effectively communicated to all key customers. The remainder of this paper will primarily describe in detail how PMCM has been and continues to be validated at JPL. To better understand the validation process it is necessary to begin with a basic understanding of PMCM.

PROJECT MISSION COST MODEL

The key features of the model are:

- Cost based on a system of equations that map to a full cost-accounting comprehensive work breakdown structure **(WBS).**
- Maximum of objective inputs that tie directly to design parameters. Prefer NO subjective inputs
- Model **has** to b.e accessible to engineers to support review and model buy-in. This means that CERs should be strictly linear unless reduction of R^2 **and** F-stat are severe.
- Probabilistic inputs and outputs
- Data used to calibrate the model reflects the integration of historical **data,** detailed subsystem level models, subsystem level databases, and expert opinion based on an integrated full life cycle mission design.

Data. The current version of PMCM is based on 60 Team X studies. These studies include proposals and conceptual design studies for potential missions e.g.:

- Mercury Orbiter
- Comet Sample Return
- Jupiter Probe
- Neptune Orbiter
- Europa Orbiter and Lander

- Jupiter Polar Flyby
- Asteroid Rendezvous
- Titan Probes/Lander
- **Solar** Sail
- Venus Aerobot
- Io Volcanic Observer
- Pluto Lander

WBS. The architecture for PMCM is a **full** cost-accounting comprehensive work breakdown structure **(WBS).** Obviously, at **JPL** this is adapted to space exploration (see Figure 1 for a standard Team X **WBS** with examples of the cost for a typical mission). The WBS is used **as** a template for capturing all Team X subsystem cost estimates

Wrappers. The following WBS elements are incorporated **as** percentages of the core model cost estimates. These are frequently called wrap-around functions or secondary relationships. These include:

- Project Management
- Outreach
- Mission Analysis & Engineering
- Science Team

Spacecraft. Their input into relevant independent variables was gathered. Then these engineers assisted the cost team in assembling a comprehensive database for each subsystem that included all possible technical parameters that could impact cost. The subsystems and elements that were assessed this way included:

- Attitude Control (ACS) (hardware & software)
- Command & Data **Handing** (CDH) (hardware & software)
- Telecommunications
- Power
- Propulsion
- Structures, Mechanisms, & Cabling
- Thermal Control
- Assembly, Test, Launch Operations

A mapping of the design (input) parameters used for each **of** the spacecraft subsystems is provided in Tables 2a and 2b. In addition to the parameters summarized below there is **a** relatively simple **mass** based cost equation with fewer design parameters for each subsystem which provides increased cost model and tool flexibility. **Both** models forecast total costs equally well, but the version presented here is more descriptive and supports more sophisticated trade-off analysis.

Payload. The payload instruments **CERs** in WBS **4.0** are a linear multivariate statistical model generated fiom 95 NASA payloads launched since 1988. Sixty-five randomly selected data points were used to generate the model; the remaining **30** points were used for validation. Inputs are all objective and cover designs ranging in size from about 1kg to 2000kg **and** design life fiom weeks to over **8** years. The Payload model was validated several years ago and the results are presented **in** (Warfield and Roust, ***1998).***

		Cart (FY 98 $M)
1.0	**Project Management**	**5.8**
1.1	Project Manager & Staff	3.0
1.2	Administration & Control	Incl Above
1.3	Mission Assurance	Incl Above
1.4	Outreach	23
1.5	Launch Approval	0.5
2.0	**Science**	5.0
2.1	Science Investigators	Incl Above
2.2	Science Teams	Incl Above
2.3	Science Analysis	Incl Above
3.0	Project & Mission Engineering	2.6
3.1	Project Engineering	Incl Above
3.2	Mission Analysis	Incl Above
4.0	**Payload**	79.1
4.1	Payload Management	0.5
4.2	Payload Engineering	1.4
4.3	Instrument (including I&T)	8.0
4.4	Aerobot (incl deceleration system)	620
4.5	Instrument Contractor Fee	7.2
5.0	**Carrier Spacecraft**	**42.8**
5.1	Spacecraft System Management	0.8
5.2	Spacecraft System Engineering	0.6
5.3	Subsystems	37.4
5.3.1	Attitude Control	5.8
5.3.2	Command & Data	2.1
5.3.3	Telecommunications	63
5.3.4	Power	53
5.3.5	Propulsion	5.2
5.3.6	Structures, Mechanisms, Cabling	7.4
5.3.6.1	S/C Mechanical Build	23
5.3.7	Thermal Control	2.2
5.3.8	Software	0.6
5.3.9	Launch Vehicle Adapter	0.2
5.3.10	Other	
5.4	Contract Management	03
5.5	Contract Fee	3.7
6.0	**ATLO**	4.8
6.1	Integration & Test Management & Planning	Incl Above
6.2	System Integration & Test	Incl Above
6.3	Launch Operations	Incl Above
6.4	Support Costs	Incl Above
6.5	Spacecraft Integration & Test Support	Incl Above
7.0	**Mission Operations**	8.6
7.1	Ops Management & Infrastructure	1.2
7.2	Mission Operations Plan	0.8
7.3	Ground Software Development	5.6
7.4	Data Processing	0.6
7.5	Launch + 30 Days	0.4
8.0	**Launch Vehicle**	**48.0**
	Project Total (no LV, no reserves)	**148.7**
	Launch Vehicle	**48.0**
	Reserves @ 20%	29.7
	Total Project Cost	226

Figure 1 - APDT WBS for a Sample Mission

MISSION AND DESIGN PARAMETERS	ACS	CDH	Tele-com	Po-wer
Pointing Knowledge (arcsec)	X			
Mission Class > C (yes/no)	X			
ACS Design Heritage (New, Minor Mods, Identical)	X			
No. of HW types	X			
ACS Flight Spares (yes,no)	X			
GSE Free to Project (yes,no)	X			
Gimbal/Actuator (yes,no)	X			
Reaction Wheels (yes,no)	X			
Star Tracker (yes,no)	X			
Rendezvous/Docking (Yes/No)	X			
ACS Software on Board (Yes/No)	X			
Autonomous ACS Software (Yes/No)	X			
CDH Redundancy		X		
Data Rate (kbps)		X	X	
Telecomm. Power (W)			X	
SC Antenna Diameter (m)			X	
SC-Earth Range (AU)			X	
Telecomm Band (S/X/Ka, UHF, Optical)			X	
Telecomm Redundancy (Single, Partial, Double)			X	
Power Source (Solar, Nuclear-Thermal, Other, Battery)				X
Solar Array Type (None, Si, Adv. Si, GaAs)				X
Beginning of Life Power (W)				X
Number of General Purpose Heating Sources (Nuclear)				X
Solar Array Area (m^2)				X
Battery Size (Watt-hours)				X
Battery Type (None, Li-ion, Li-poly, Li-SOCl2, Other)				X
R2	88.1	62.3	89.0	95.7
F-ratio	45.3	15.9	32.3	129

Figure 2a - Model Input Summary

MISSION AND DESIGN PARAMETERS	Structure	Propulsion	Thermal	Mechanical Build Up
Specific Impulse (I_{sp}) (sec)		X		
Propellant Mass (kg)		X		
SC Dry Mass	X		X	X
Structure Mass	X			
No. of Mechanism Des/Types	X			
Mechanisms No. of Low Complexity	X			
Mechanisms No. of Nominal Complexity	X			
Mechanisms No. of High Complexity	X			
SEP Propulsion (yes, no)	X			
Destination (Mercury/Sun, Jupiter/Pluto, Other)			X	
Cold Body Lander (yes, no)			X	
No. of Instruments	X			
Extra Stages (yes, no)				
R2	84.4	72.7	83.0	82.2
F-ratio	109	27.7	473	158

Figure 2b - Model Input Summary

VALIDATION PROCESS

The development and validation process utilized was as follows:

1. Subsystem CER Development and Validation
    a. Jointly develop list of design and cost parameters with respective subsystem engineers
    b. Develop Version 1 of CERs using linear regression analysis
    c. Review results with subsystem engineers to determine that parameter coefficients intuitively make sense.
    d. Revise CERs
2. Formal Validation of Total Mission Cost
    a. Statistically validate that model estimates are consistent with actuals and with grass roots estimates for JPL Flight Projects and Phase A equivalent proposals
3. Major Stakeholder Review
    a. Conduct formal review of model by senior technical staff and managers
    b. Revise CERs
    c. Regression test CERs

Subsystem CER Development and Validation

The first step was to interview the subsystem engineers in order to identify all key design parameters, which were considered to be significant cost drivers for each subsystem. At the end of the interviews, over **200** potential design based cost drivers had been identified and ***55*** potential studies. Of the **355** possible data point-subsystem combinations (7*55), only **72** were removed, yielding **from 28** to **5**1 records per subsystem. Most of the removed data points were removed because they were very large outliers with insufficient frequency of occurrence to identify a cost driver that could explain the impact of the unusual technologies or environments:

- No subsystem: 19
- Duplicate of included point: **24**
- Missing Cost Data: **13**
- Missing Technical Data: 1
- Unusual Technology: **7**
  (1 obscure CDH technology used in only one study, 1 **CIS solar** array, **1** thermal-mechanical-electrical power generation, **2** HAN/TEAN propulsion, **2** second-generation micro-spacecraft structures)
- Unusual Environment: **2** (Thermal & C&DH on Venus Surface)
- Unusual Application: **1** (Propulsion system used only for inflation purposes)
- Early study that may not assume **FBC** processes: **3**
- Suspected data errors **that** could not be verified or corrected: **2**

The **200** design parameters resulted in approximately ***50*** cost drivers. The initial subsystems **CERs** were derived using multivariate linear regression. Cost variables were selected based on an F-ratio > **10, an** adjusted R^2 > **75%,** and a student t-ratio > 1.95 (5%). Variables whose direction **was** inconsistent with engineering principles were dropped.

The next step was to review the individual, statistically derived CER's with the cognizant subsystem engineers. **This** helped ensure the scientific foundation of the CER's **as** well **as** helping to get the correct technical inputs for each CER. After the subsystem engineers reviewed their respective CERs it was decided to keep some design parameters with low t-ratios if the variable was a major design parameter **and** the coefficient was consistent with engineering judgment

An example of the power subsystem CER results are displayed in tabular form **in Figure 3** and graphically in Figure **4.** While the subsystem engineer used many other variables in determining his bottom-up cost estimate, it was found that these five variables explained 95% of **the** total variation in the data. These results were carefully reviewed and discussed between the cost modeler and the power subsystem engineer.. Note that the 'Battery Only' variable was kept in the equation even though it failed the 5% t-test.

Variable	Coefficient	t-ratio	Significance
Constant	$5,477 K	6.25	< 0.0001
Battery Only	- $4,149 K	-1.77	0.0887
Array Area (m^2) – Si	$ 253 K	4.14	0.0004
Array Area (m^2) – GaAs	$ 440 K	4.9	< 0.0001
Array Area (m^2) – Adv. Cells	$ 445 K	22.8	< 0.0001
Number of GPHS	$4,854 K	13.7	< 0.0001

Figure 3: Power Subsystem Final Regression Results

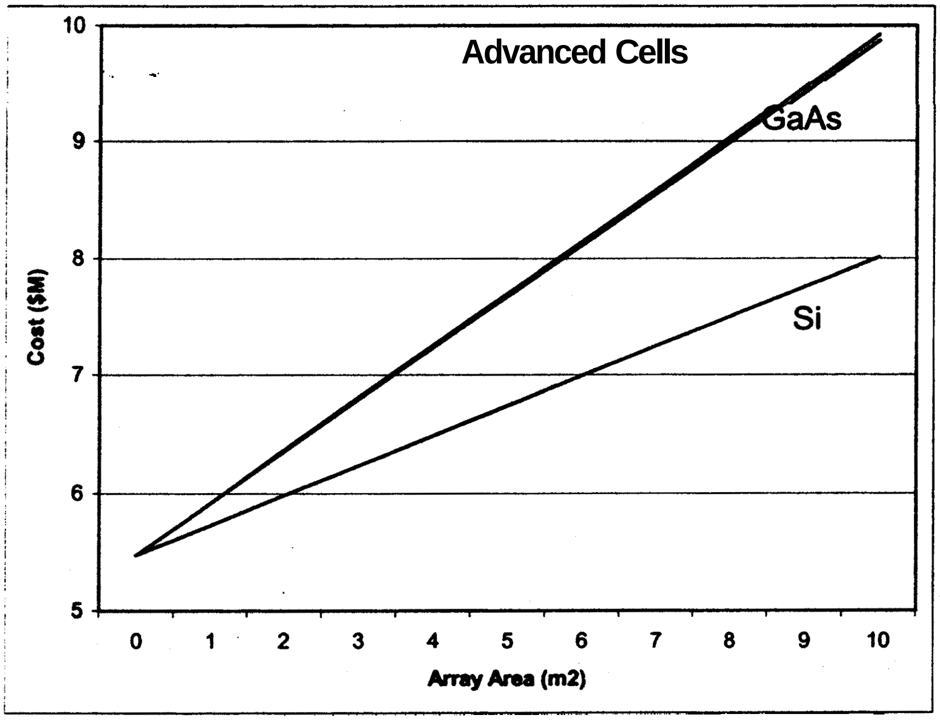

Figure 4: Cost vs Solar Array Area by Cell Material Type

FORMAL VALIDATION.

After the review by the subsystem engineers, the second major step in the validation process was to come up with a number of recently completed JPL missions, and then to attempt to replicate the costs of these missions with the model. Unfortunately, insufficient subsystem cost actuals were available to formally validate the model at the subsystem level. At the time this validation was completed even obtaining sufficient actual data at the spacecraft level was difficult. Hence, the main formal validation was conducted at the total mission cost level. Due to the small number of missions completed, several missions that were well into development were also included. The missions included are:

- Mars Pathfinder - completed rover mission on Mars (launched in 1996)
- Mars Global Surveyor - completed mapping of Mars (launched in 1996)
- DS-1 - advanced technology demonstration (launched in 1998)
- Stardust - comet sample return (launched in 1999)

- Genesis - solar wind sample return (launches in 2001)
- Cloudsat - measures the evolution galaxies (launches in 2001)
- Deep Impact – In Phase B. Also estimated the Impactor separately
- Inside Jupiter – In Phase A
- Cassini – last of the great spacecraft
- Mars 98 – two mission in one, an orbiter and a Polar Lander. Failed mission objectives

Reference Mission	± Percentage difference between actual costs and estimated costs
Mission 1	-19.0%
Mission 2	-2.3%
Mission 3	-8.2%
Mission 4	-1.6%
Mission 5	-5.5%
Mission 6	16.2%
Mission 7	53.1%
Mission 8	0.4%
Mission 9	23.2%
Mission 10	89.5%
Mission 11	89.4%
Mission 12	-45.6%

Figure 5: Percentage Comparison of PMCM estimate to Actual/Planned JPL Mission Cost

Although, not representative of current JPL missions, the Cassini mission (Mission 12) was added to the set for comparison purposes. The results suggest that Cassini while still very expensive by today's standards (Cassini had 8 to 9 years in development with 500-700 work years of effort) would have cost 46% less than it did when originally developed in the late 80's through early 90's. The PMCM database contains missions with a maximum of 3 to 4 years in development. It might have been possible to develop Cassini under these conditions. A graphical version of the results is displayed in Figure 6. On the vertical axis of Figure 6 is the actual cost and on the horizontal axis is the model-estimated cost. If these matched exactly, they would fall on the diagonal line. Points above the diagonal designate missions for which the model under estimated the costs and points below the diagonal designate missions where the model over estimated the actual costs. The Cassini mission is not shown due to scaling problems in displaying the graph. Interestingly, the missions which fell the furthest below the line and which reveal a significant over estimate by the model are the two Mars 98 missions which failed.

Constructing a formal statistical test is more difficult than it might appear because the data for the model was generated by JPL's Team X and hence are all estimates - therefore it is unlikely that the underlying data distributions for the model are the same **as** for the actuals. At this point however, we will test the ability of **PMCM** to predict the actual cost based on the following

$$(\Sigma(\text{Model-Est} - \text{Mission\_Actuals}))/n)/\ \sigma/(n)^{-1/2}$$

This **is** a t-test for whether the difference between the estimate and the actuals is zero and hence at a minimum provides a test **of** model estimates bias. Excluding the **3** missions which a-priori should be from a totally different population (Mission **10,** 11 and Cassini) the results yield a mean difference of 0.5 ($500K) with a small sample standard deviation of 6.0 $M. Therefore, we accept the hypothesis that there is no significant difference between the model estimates and the actual mission costs. All **3** of the outlier missions are more then **3** standard deviations fiom the population mean and hence one should reject that they are fiom the same population.

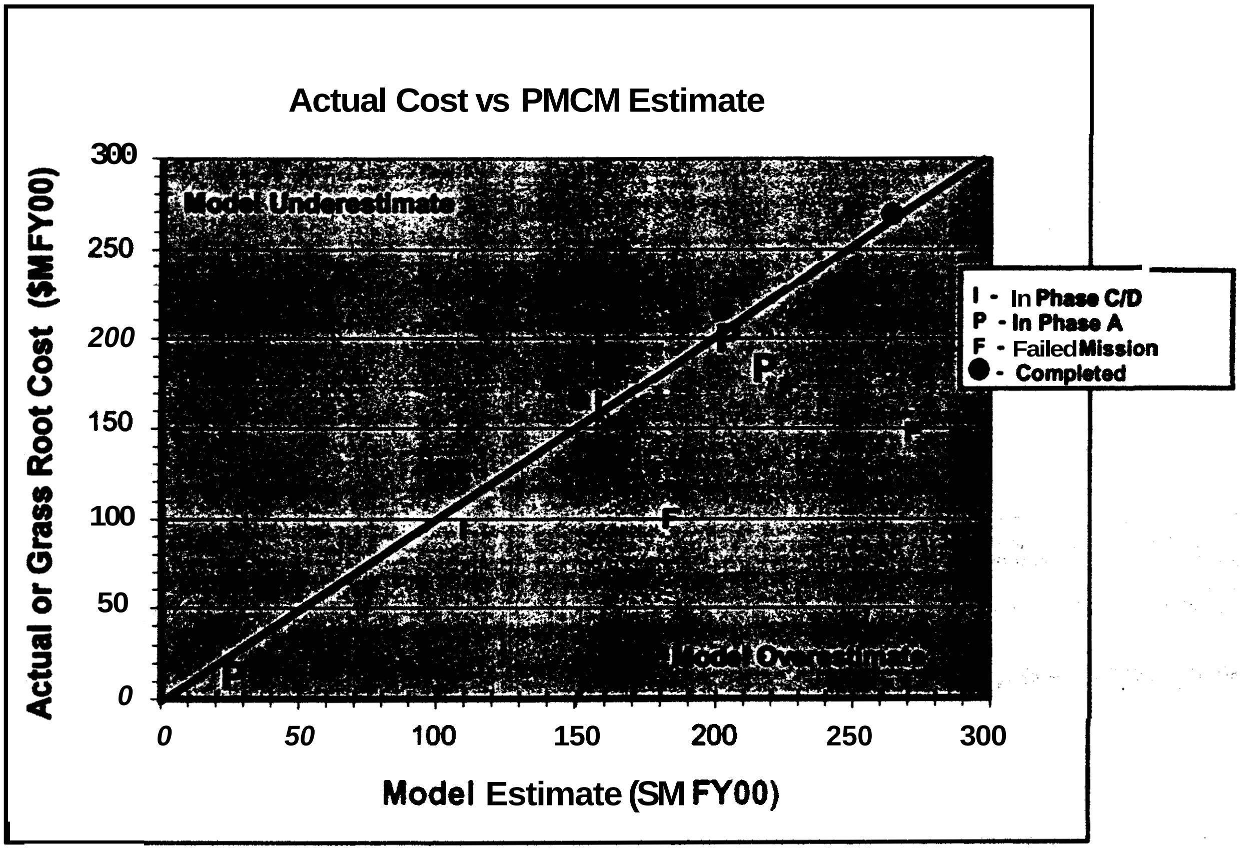

Figure 6: Actual Cost vs PMCM Estimate

Major Stakeholder Review

The **last** step **was** to present these results to a formal review board made up **of** major JPL stakeholders in the estimation and mission development processes. The review board was chosen from systems engineers and managers at JPL who have had long-term flight project. experience. The objective of the review was to obtain support fiom the major stakeholders and also to make certain that major design parameter had been inadvertently left out. **A 3-hour** review **was** held in which the review board **was** walked through each major equation with detailed explanations as to how the CERs were constructed and verified. To be able to conduct this type of review means a cost model must be relatively easy to understand and use. At the end of the review there were requests to analyze if three additional cost drivers could be added.

PMCM APPLICATION

PMCM is used on a regular bases in Team X as back up estimate and to assess the reasonableness of the grass roots estimates for Discovery proposals in 1998 and 2000, as well as to evaluate other proposals. The results for the 2000 Discovery Step 1 are displayed in Figure 7. It is interesting to note that there is an average over estimate by the model of $19M with double the variation of that observed with the actuals, which differed by only $500K. This is consistent with the expectation that proposals will tend to underestimate to sell the proposed mission. Note also that there *appears* to be bias in the data in that a majority of the proposals under ran the model estimates. This differs from the actuals, which were evenly distributed between under and over model estimates.

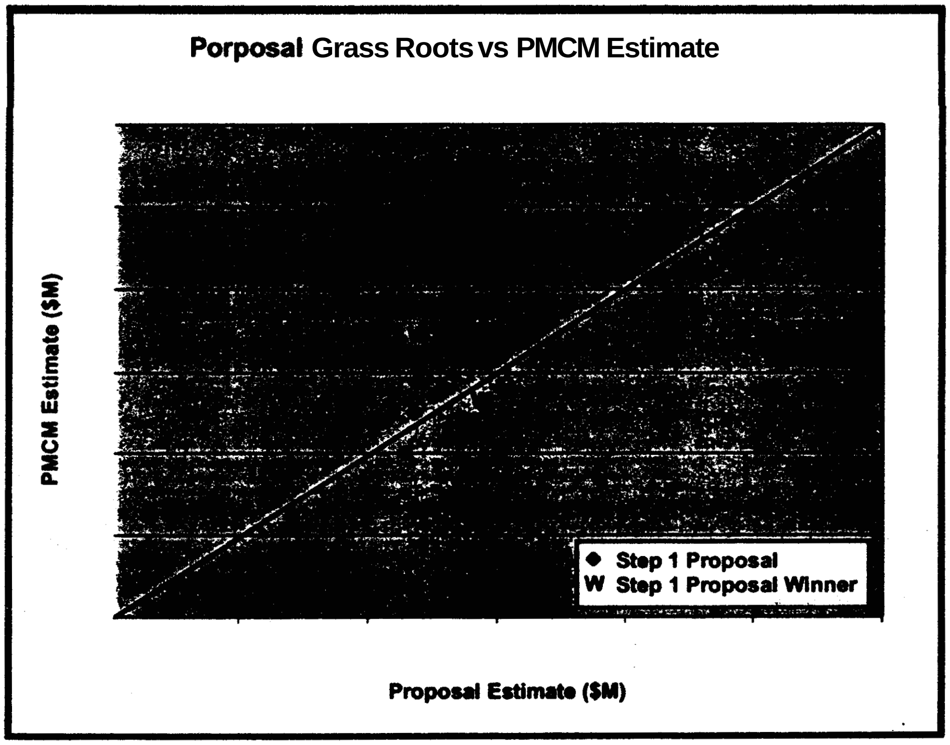

Figure 7: Discovery Proposal Estimates vs PMCM Estimates

FUTURE WORK

It is hoped that other companies that assess space mission costs will adopt similar techniques to those described in this paper. Lastly, it is recognized that once the model is validated it will enter a maintenance mode. In this mode, it will have to be updated and re-validated about once a year so that it reflects the latest technology and cost data. Future validations will be done at the spacecraft and subsystem level as the data becomes available. We are currently looking into the use of a technique known as boot strapping which is designed for dealing with estimation under conditions of small samples. It utilizes assumed information as to the shape sign of parameters in a regression equation. By adding in these constraints, less data is required in order to obtain a *'good'* estimated equation.

Another concern that remains is the incorporation of design parameters into cost estimating relationships that explicitly account for the impact of changes in one subsystem or element on other subsystems or elements. Related to this is the problem of characterizing correlation between WBS elements. This is an issue when performing Monte Carlo simulation since correlation impacts the spread of the resulting probability distribution. Future work will include these features including the construction of a correlation matrix based on each element's coefficient of determination with respect to every other element.

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BIOGRAPHIES

Name: Dr. Jairus **M.** Hihn
Business Affiliation:
Jet Propulsion Laboratory
4800 ***Oak*** Grove Drive
Pasadena, CA 91109
MS 301-180
Phone Number:
(818) 354-1248
Fax Number:
(818) 393-9815
E-mail Address:
jhihn@jpl.nasa.gov

Biography: Jairus Hihn **has** a Ph D in Economics with principal application **areas** in econometrics and mathematical economics. His dissertation **used** Monte Carlo methods in developing **an** R&D project selection model. Jairus is the lead software cost analyst at JPL. He **has** been providing cost estimation support to JPL's Deep Space **Network and** flight projects for the past ten years and **more** recently has been working with JPL's Advanced Projects Design Team, **as** well **as** developing mission level cost estimation models. **Dr.** Hihn was on the faculty at the University **of** California - Berkeley in the Department of Agricultural and Resource Economics where he co-developed a new statistical technique based on the semi-variance of a probability distribution for use in estimating agricultural production and income risks. He was the co-author on several papers, which formally applied catastrophe theory to **the** analysis **of** political instability in third **world** countries using **both** non-parametric and maximum likelihood methods. He has extensive experience in simulation **and** Monte **Carlo methods with** applications in **the** areas **of** decision analysis, institutional change, cost modeling, **and** process models.

Name: Leigh Rosenberg
Business Affiliation: Jet Propulsion Laboratory

Biography: Leigh Rosenberg is a Senior Project Cost Analyst and the lead Advanced Projects Design Team cost engineer at JPL. He **has** worked at JPL in cost estimation and systems engineering for the last **23** years. He has created the DNP cost methodology **and has** coordinated the cost estimation of various competitive proposals including the Stardust project. He previously supervised **the** Project Engineering group **of** ***JPL's*** Systems Analysis section. **Mr.** Rosenberg has previously worked **for** the Federal Government at the Interstate Commerce Commission, and **for the** MITRE Corporation. He **has an** MS in Operations Research and Industrial Engineering from **the** University **of** Massachusetts and a BA in Mathematics from **Queens** College of the City University of New York.

Name: Kevin Roust
Business Affiliation: Jet Propulsion Laboratory

Biography: Kevin Roust is a Project Cost Analyst and a member of the Advanced Projects Design Team at JPL. He **has a BS** in economics **from** the California Institute **of Technology.** Mr. Roust **has been** involved in cost **tool** development for **the** Advanced Projects Design Team, and **other** computer simulation design work for JPL's re-engineering effort.

Name: Keith Warfield
Business Affiliation: Jet Propulsion Laboratory

Biography: Keith Warfield is a Senior Project Cost Analyst at the Jet Propulsion Laboratory working with **the** Advanced Projects Design Team. He holds a B Sc in Engineering and Applied Science fiom the California Institute **of** Technology. Prior to his work **as** a cost analyst, Mr. Warfield worked **for** more than a decade in engineering roles on several science instruments including the Satellite Test **of** the Equivalence Principle, the **Mars** Observer Pressure Modulator Infrared Radiometer, the Topex Microwave Radiometer, the UARS Microwave Limb Sounder, and particle detectors **for** the **Stanford** Linear Accelerator.