Parametric Cost Modeling of Space Missions Using the Develop New Projects (DNP) Implementation Process

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Abstract. This paper presents an overview of a parametric cost model that has been built at JPL to estimate costs of future, deep space, robotic science missions. Due to the recent dramatic changes in JPL business practices brought about by an internal re-engineering effort known as develop new products (DNP), high-level historic cost data is no longer considered analogous to future missions. Therefore, the historic data is of little value in forecasting costs for projects developed using the DNP process. This has lead to the development of an approach for obtaining expert opinion and also for combining actual data with expert opinion to provide a cost database for future missions. In addition, the DNP cost model has a maximum of objective cost drivers which reduces the likelihood of model input error. Version 2 is now under development which expands the model capabilities, links it more tightly with key design technical parameters, and is grounded in more rigorous statistical techniques. The challenges faced in building this model will be discussed, as well as it's background, development approach, status, validation, and future plans.

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. JPL's record of successful missions from Explorer to Viking, Voyager, and Mars Pathfinder has earned it a world wide reputation for successful completion of highly complex scientific space projects.

History 1965-1995. From the period of the mid-1960's until the early 1990's, JPL's major missions could be characterized as usually having 1 or 2 spacecraft per mission, an average development cost of over $739M (FY 98) not including the launch vehicle, a development period of about 6 years, and an average post-launch operations cost of about $30M/year. There were 16 missions over the 29 year period from 1964 to 1992. Project system designs were allowed to be maximized for science objectives with minimal concern for cost constraints. Not surprisingly, final project costs were typically double the original estimates. No projects were canceled because of cost increases. Preceding these missions about 5 to 10 proposals a year were produced at JPL.

Starting in the mid-1990's as US Federal budget deficits became more of a national concern, space project costs also came under closer scrutiny. Cost became a major design parameter much as any other spacecraft subsystem (i.e., power, telecommunications, etc.) that would be evaluated during the systems engineering design process. Furthermore, instead of missions just being given outright to JPL, many new starts were based on winning a competition judged in part on cost and estimation credibility. The average development cost of current missions is now about $165M, the development time is about 3.5 years, and the average operations cost after launch is $4M/year. These costs represent significant reductions from the previous, standard way of doing business at JPL.

Furthermore, there is an increase in the number of missions launched each year. Instead of the previous 1 mission every two years, 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 to cost, other factors that have made these recent missions more cost efficient are: increased inheritance from previous missions, reduced redundancy (increased risk), and more work done in parallel during the development cycle. In this paper this latter period is referred to as the "faster, better, cheaper" (FBC) way of doing business at JPL.

Figure 1 contains the historic cost trends of JPL space mission development costs (mission costs up to launch). Figure 2 contains the historic cost trends of JPL annual space mission operations costs.

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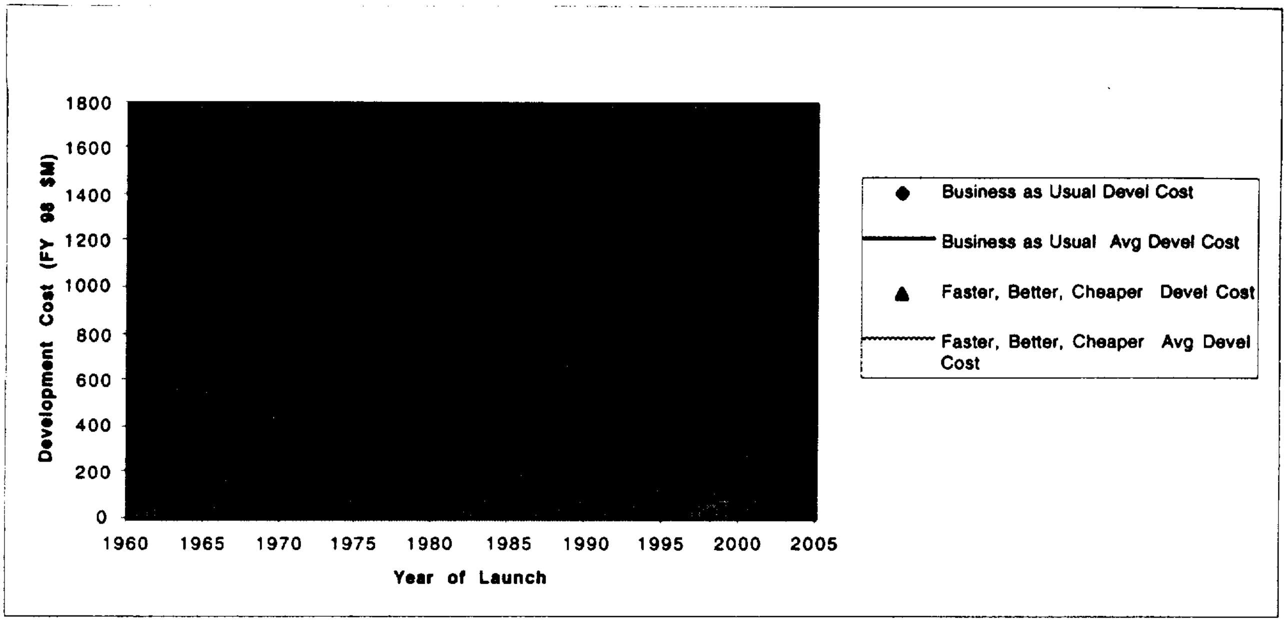

Figure 1: JPL Deep Space Mission Development Cost Vs Launch Year

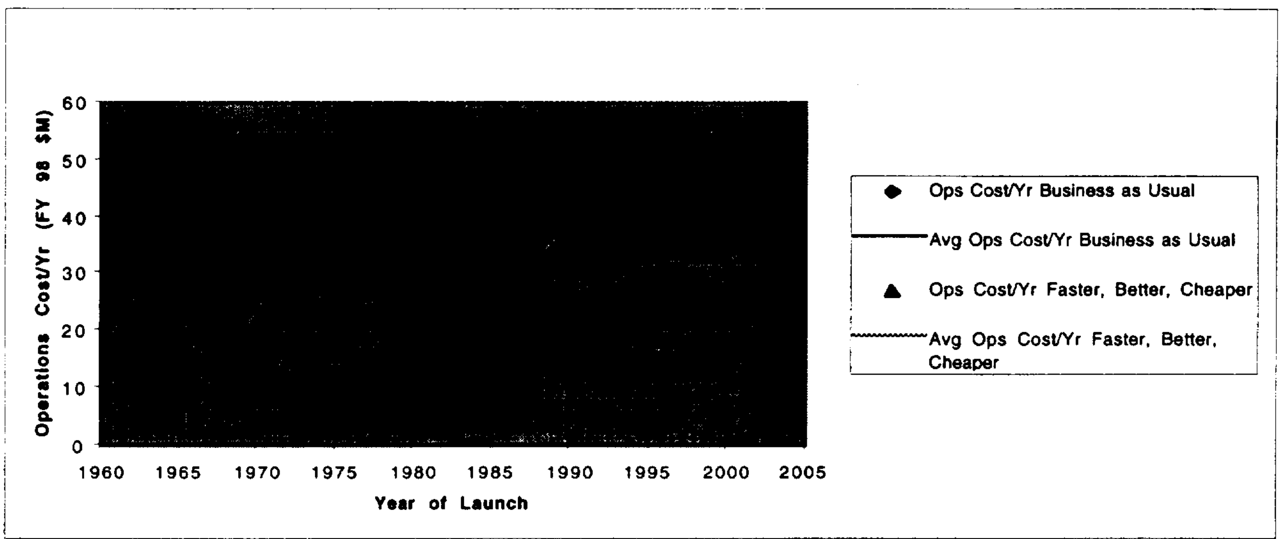

Figure 2: JPL Deep Space Mission Operations Cost/Yr Vs Launch Year

History Post 1995. In 1995, as a way to deal with the large number of proposals being generated, JPL formed an Advanced Projects Design Team (APDT). This multi-disciplinary systems engineering design team takes the design process one step further than FBC for the next generation of deep space designs that will be implemented in the early 21st century. This newer process is the result of re-engineering the entire space mission design process at JPL and is known as "Develop New Products" (DNP). It assumes a rapid development schedule where the spacecraft development phase takes place within 2.75 years or less. The development team staffs up much faster, there is widespread use of behavioral and cross-cutting computerized models (which will reduce the need for work force intensive change control boards, etc.), and there is a minimization of written requirements documents. This process also includes advanced technology gains that are expected to be made by the proposed X2000 mission as well as several others (Mars Pathfinder, Mars Global Surveyor, New Millennium). For custom spacecraft, it is expected that the DNP process can save 20% to 30% of the cost over current faster, better, cheaper approaches. With the implementation of DNP it should be possible to perform significant science in the far reaches of the solar system for life cycle costs in the $150M to $300M range (excluding launch vehicle).

When the magnitude of 50 to 80 proposals supported annually (many of which are going to be competitively judged) and the addition of a new, unproven way of developing and operating deep space missions are weighed, it is obvious that a parametric model that gives reliable costs without convening the entire 15-member APDT for every mission study would be a very valuable, cost effective tool. The problem is, of course, that useful historic data on which such models are typically constructed does not exist, since this new way of doing business is different than that of the past. Even the missions starting in 1992, which are far closer in concept to DNP, have not all yet flown. So even if the current design process was the same as DNP, the cost (and design) based on them might not be very accurate.

DNP COST MODEL VERSION 1

Seventeen DNP studies were used as the basis for the first version of the cost model which was built in late 1997. The model incorporates a Monte Carlo simulation that can operate on ranges of input values. For a detailed description of Version 1 of the model, the DNP process, and JPL's APDT see Rosenberg, 1998. The key features of version one of the DNP cost model are:

- Cost based on a system of equations that map to a full cost-accounting comprehensive work breakdown structure (WBS).
- 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.
- Maximum of objective inputs
- Probabilistic inputs and outputs

Even though the model was built largely on expert opinion in the absence of real data, the developers feel that the model resulting from this is quite satisfactory. There are several reasons for this. First, the expert engineering opinions contain factual information such as actual prices of hardware. Second, these experts have experience with real-life space projects. Third, their organizations stand behind these engineers as recognized experts.

Version 1 of the model has been validated by comparing it with the cost estimates of the recently completed 1998 Discovery - Step 1 proposal process. Its cost estimates were within 15% of proposal grass roots costs in 12 out of 16 JPL proposals. The average cost difference for all the proposals was 8.5%. Version 1 was also partially validated by testing it for two actual, ongoing JPL projects, Stardust and Genesis. On these two missions the model was within 5% of the current project budgets. Stardust and Genesis are FBC projects so the model should have estimated a lower cost. However, both projects have high inheritance, a major DNP factor, so the 5% estimates were felt to be reasonable.

The results from the grass roots cost estimates of the Discovery proposals and the actual costs of Stardust and Genesis indicate that independent engineers who are not on APDT and who, for the most part, do not work at JPL are arriving at about the same costs as the APDT subsystem engineers as replicated in Version 1 of the model.

DNP COST MODEL VERSION 2

In October, 1998 it was decided to build the next version of the model. This newer version (Version 2) includes APDT studies completed since the summer of 1997 raising the total number of studies in the data base from 17 to about 60. Another major reason for building the updated version is to enhance its use for detailed systems engineering design trade-off studies. Therefore, an attempt was made to include elemental components of the various subsystems. For instance, the power subsystem now contains explicit cost relationships for batteries, generation type, and power delivery components. Other improvements incorporated in the new version of the model include:

- Provides mass based and non-mass based (more descriptive or design parameter sensitive) cost estimates. Both forecast equally as well.
- Links to the cost estimating relationships that enable the model to interface with other computer-based design tools such as JPL's Project Trades Model and JPL's other DNP automated tools.
- A reduced, simplified version of the model that can easily be transferred and be used by project managers who can operate it as a DNP tool without expert guidance,
- A formal validation based on 7 actual mission costs, and the approval of a standing, well-regarded peer review committee.

Model Approach. The first step was to start with the work breakdown structure (WBS) that APDT uses for DNP studies. A WBS is a representation of all the steps that must be performed in carrying out a project. Obviously, at JPL this is adapted to space exploration (see Figure 3 for a standard APDT WBS with examples of the cost for a typical mission). The WBS was used as the template by which the various cost elements of a space project would be represented. (Version 2 utilizes the same WBS as Version 1.)

		Cost (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	2.3
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)	62.0
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	6.3
5.3.4	Power	5.3
5.3.5	Propulsion	5.2
5.3.6	Structures, Mechanisms, Cabling	7.4
	5.3.6.1 S/C Mechanical Buildup	2.3
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	0.3
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 3 - APDT WBS for a Sample Mission

At the time the Version 2 effort started, APDT had done about 60 DNP studies. These studies include such potential missions as:

- Mercury Orbiter
- Comet Sample Return
- Jupiter Probe
- Neptune Orbiter
- Europa Orbiter
- Europa Lander
- Jupiter Polar Flyby
- Asteroid Rendezvous
- Titan Probes/Lander
- Solar Sail
- Venus Aerobot
- Io Volcanic Observer
- Pluto Lander

These were used as the basis for the model. It is recognized that a new process must be gone over many times before it becomes standardized. This would typically cause the early studies to be discarded. On this second version the cost analysis team was able to eliminate early studies that were not consistent with later studies, eliminate missions that were not a full implementation of DNP, eliminate missions that were very similar to other missions, and to correct for unusual data entries.

Model Structure. Once the data set was chosen, APDT subsystem engineers were brought into the process. 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 Handling (CDH) (hardware & software)
- Telecommunications
- Power
- Propulsion
- Structures, Mechanisms, & Cabling
- Thermal Control
- Assembly, Test, Launch Operations (ATLO) (includes integration & test)
- Ground system development
- Operations

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

Payload instruments are modeled with the APDT Instrument Cost Model. This model is a linear multivariate statistical model generated from 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 in design life from weeks to over 8 years. It was last updated in 1998. It can be used both as a stand alone instrument estimation tool, and as an element within this paper's total life cycle model (Warfield and Roust, 1998).

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 (Single String, Dual String)		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

Figure 4a - Model Input Summary

A mapping of the design (input) parameters used for each of the spacecraft subsystems is provided in Tables 4a and 4b. 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.

MISSION AND DESIGN PARAMETERS	Struc-ture	Propul-sion	Ther-mal	ATLO
Specific Impulse (I_{sp}) (sec)		X		
Propellant Mass (kg)		X		
SC Dry Mass	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			X
Extra Stages (yes, no)				X

Figure 4b - Model Input Summary

The next step was to review the individual, statistically derived CER's with the cognizant APDT 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. The final statistical fits of the CER's include linear and logarithmic equations. At this point the structure of the model with respect to primary and secondary CER's was reviewed with knowledgeable systems engineers who are also members of APDT or the DNP team.

For the secondary CER's not much primary test data existed, so these were built based on input from cognizant engineers plus generic factors from previous projects and various recent proposals at JPL. Figures 4a and 4b gives the independent variable inputs that are currently utilized by the DNP cost model. Note that each engineering design change must be converted into the independent variables that the model uses.

Subsystem Detail. As an example of how the model has evolved, an overview of the Attitude and Control Subsystem (ACS) is presented in Figures 5a and 5b. Subsystem level equations support subsystem level trade-offs. Figure 5a contains a comparison between the Version 1 and Version 2 mass based cost equations. Here it can be seen how the basic forecasting accuracy between the two models is equal. The coefficients on the common variables are also very close. Version 2 has added information on design heritage and mission class, which is known very early in the design and planning stage.

Variable	ACS V 1.0	ACS V 2.0
Constant	9.7	9.5
ACS Mass	0.24	0.19
Pointing Knowledge	-0.004	-0.003
Downlink Data Rate	0.006	
New_Design		5.75
Identical_Design		-2.17
Mission_Class>C		3.95
R^2	86.4%	82.6%
F-Stat	32.9	29.5
Sample Size	16	31

Figure 5a - Model Input Summary

Figure 5b Presents the element level equations for ACS. The increased detail of the element level equations make it possible to analyze cost impacts for internal ACS trade-offs, especially between hardware and software. Here it can be seen that while there is an increase in the descriptive quality of the model the forecasting performance has decreased as the R^2 has decreased from around 80% to about 70%.

All of the equations in the DNP cost model are what are commonly called surface response models. This means that the equations should only be used for complete designs and that marginal changes in individual parameters do not always reflect the actual cost changes due to the corresponding adjustments in other spacecraft elements and subsystems.

Variable	ACS Sys. Eng & Anal	ACS Integration & Test	ACS HW	ACS SW
Constant	0.93	0.86	1.76	1.91
Mission Class>C	0.79	0.49	2.20	.50
New Design	1.06	0.33	1.77	
HW Types (No.)	0.10	0.03	0.32	
Identical Design	-1.17	-0.32		-1.02
Pointing Knowledge	-.0001	-.0002		-.0006
Docking Required	0.09		2.12	
Reaction Wheels			3.65	0.59
New Design & Automation SW				1.52
Actuators			2.76	
GSE Provided			-0.90	
No Spares			-1.40	
R^2	74.0	67.6	68.2	68.8
F-Stat	15.2	13.5	22.5	14.2

Figure 5b - ACS Model Input Summary

Validation. After the review by the APDT engineers another step in the validation process has been to come up with 7 current and recently completed JPL missions that would be as close as possible to the DNP scenario, and then to attempt to replicate the costs of these missions with the model. These missions are:

- Mars Pathfinder - recently completed landing on Mars (launched in 1996)
- Mars Global Surveyor - currently mapping 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)
- Galex - measures the evolution galaxies (launches in 2001)
- Grace - produces new models of the Earth's gravity field (launches in 2001)

As this paper is being written most of the technical and cost data for these actual missions has been assembled. These test cases will be assessed starting in May.

As the results from exercising the model for actual missions are assessed and adjustments are made to it, the peer review portion of the validation will be initiated. The peer review board has been chosen from systems engineers at JPL who have long term, actual design and flight project experience. They were also chosen on the basis that they were not too familiar with the cost model. The idea is to convince them that the model is useful for their jobs. It therefore needs to be accurate, reliable, and relatively easy to understand and use. This portion of the study should be complete by September, 1999.

FUTURE WORK

Once the validation is complete, it is the objective of the model sponsors that it becomes the basis for making early and accurate estimates of project cost by JPL project managers and systems engineers. It is also hoped that other companies that assess space mission costs will adopt the techniques 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 probably about once a year so that it reflects the latest technology and cost data.

One 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 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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