Rapid Cost Assessment of Space Mission Concepts through Application of Complexity Indices[1,2]

Craig Peterson, James Cutts, Tibor Balint, James B. Hall
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109
818-393-2481
Craig.Peterson@jpl.nasa.gov

Abstract— In 2005, the Solar System Exploration Strategic Roadmap Committee (chartered by NASA to develop the roadmap for Solar System Exploration Missions for the coming decades) found itself posed with the difficult problem of sorting through several mission concepts and determining their relative costs. While detailed mission studies are the normal approach to costing, neither the budget nor schedule allotted to the committee could support such studies. Members of the Jet Propulsion Laboratory (JPL) supporting the committee were given the challenge of developing a semi-quantitative approach that could provide the relative costs of these missions, without requiring an in depth study of the missions. In response to this challenge, a rapid cost assessment methodology based on a set of mission cost/complexity indexes was developed. This methodology also underwent two separate validations, one comparing its results when applied to historical missions, and another comparing its estimates against those of veteran space mission managers. Remarkably good agreement was achieved, suggesting that this approach provides an effective early indication of space mission costs.

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1. INTRODUCTION

In the fall of 2004, NASA began developing 13 documents, known as "strategic roadmaps," intended to outline a strategy for space exploration over the next 30 years. The Third Strategic Roadmap, The Strategic Roadmap for Solar System Exploration, focused on the strategy for robotic exploration of the Solar System. Because of exciting recent discoveries on many of the outer solar system bodies as well as the scope of investigation, the development of the Strategic Roadmap for Solar System Exploration led to the investigation of a large variety of missions. However, the necessity of planning around not only scientific inquiry but also budgetary constraints made it necessary for the roadmap development team to evaluate potential missions not only for scientific return but also costs incurred. Performing a detailed cost study for the each of the large number of missions was impractical given the time constraints involved and lack of detailed mission studies for each of the candidate missions; rather, a method of rapid cost assessment was developed by a JPL team to allow preliminary analysis. Others [1] have noted a strong correlation between complexity and cost and schedule of planetary missions. While these correlations were made after the missions had been built and flown (successfully or otherwise), it seemed likely that a similar approach could provide at least some relative cost ranking. There have been attempts to develop cost estimation relationships (CERs) based on subsystem design choices [2]. However, these CERs required more detailed information than was available, forcing the team to adopt a more high level approach. Costing by analogy has been developed [3] for small satellites however, planetary exploration missions provide such varying spacecraft requirements that there is a lack of adequately comparable missions that can be used for analogy.

This rapid cost assessment method facilitates analysis of mission costs without expending the (sometimes considerable) time and resources required for detailed cost studies. The rapid cost assessment approach makes use of cost/complexity ratings for key space mission technical and operational categories. These ratings provide numerical cost driver indices to create an estimate of a mission cost without exploring the nuances of the actual spacecraft design. In turn, such estimates can be used to develop a funding profile for a program of missions, and initial analysis of mission and program chronology, including both program initiation

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and mission frequency. In this way, rapid cost assessments made possible the efficient development of a long term expansive plan for Solar System exploration, as well as possible alternative scenarios in the face of funding changes.

2. APPROACH

The development of the rapid cost assessment method integrated two approaches for estimating mission costs: the first was estimation through mission cost indices and the second was estimation by experienced spacecraft development managers. By combining these two approaches, not only could each estimate be evaluated for accuracy, but sources of unexpected costs and greater information about the issues each mission faced in development could be explored in greater detail than if either method had been used in isolation. The process for obtaining these estimates is illustrated in Figure 1. The approach taken to develop the rapid cost assessment consisted of seven distinct steps, as follows:

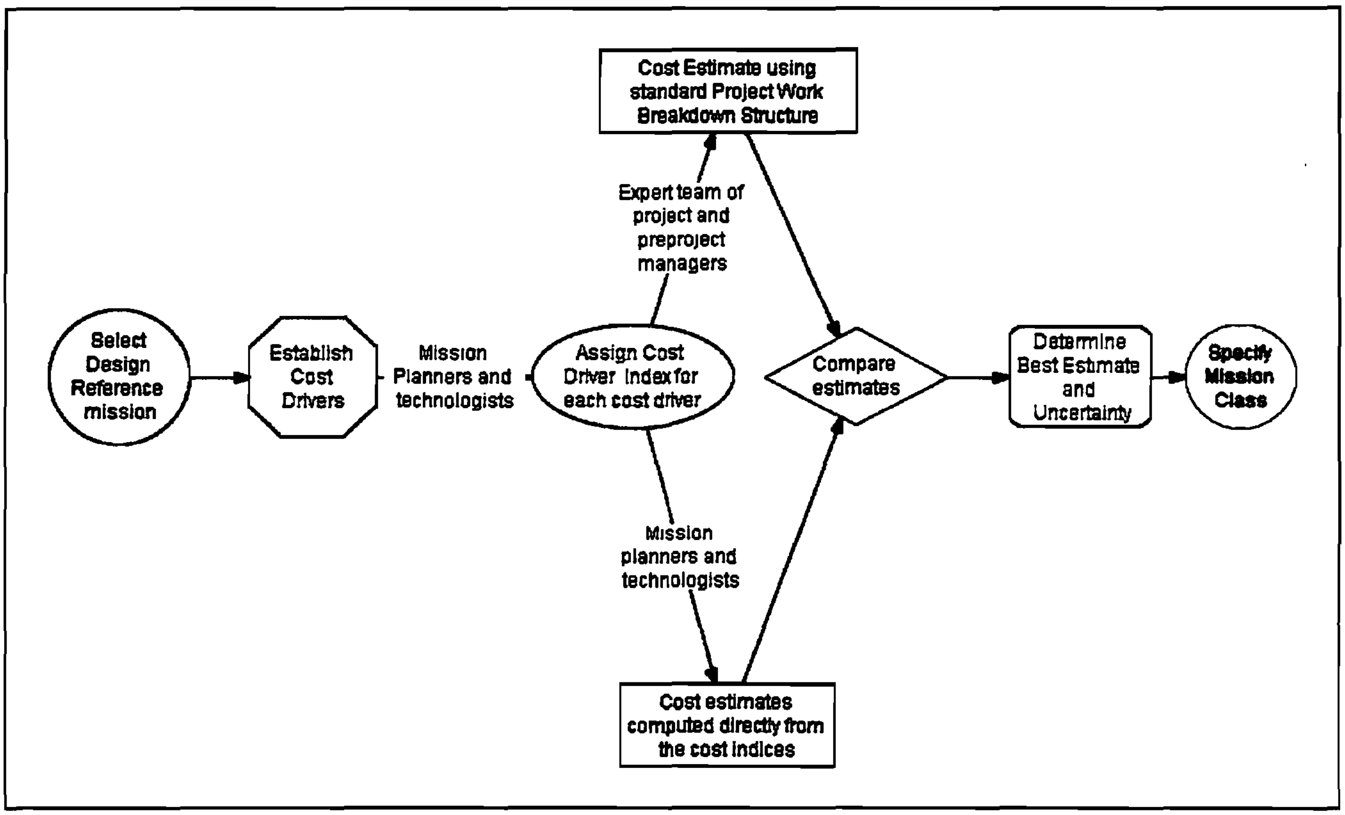

Figure 1 - Approach for developing and validating rapid cost assessments

1. A mission was selected for evaluation. In order for the rapid cost assessment to be effective, the mission it evaluated must already have outlined explicit scientific goals as well as enough formulation to identify the cost drivers for the mission.

2. Cost drivers for the mission were established. A more detailed discussion of cost drivers is included below, but simply put, cost drivers are all attributes of the mission which will affect the cost of the mission. These drivers were identified in order to create an estimate that would be an accurate predictor of mission costs.

3. A cost index was assigned to each cost driver. Once the cost drivers for a certain mission were established it was necessary to determine the magnitude of the cost each driver was likely to incur. Different missions require different levels of capabilities and complexity, and cost indices are used to anticipate these levels and predict costs accordingly. Thereby, cost driver indices provide a baseline idea of how much that capability is likely to increase the cost of the mission.

4. Two different and simultaneous approaches were taken:

   a. Cost estimates were computed using standard project work breakdown schedules. An expert team of experienced project and preproject managers was briefed on the details of the mission, and then computed an estimate of costs for different aspects of the mission design. Standard "wraps" used to quantify costs not covered by the expert team estimates were then evaluated, and the wraps and estimates combined to create a total estimate of the mission costs.

b. Cost estimates were computed directly from cost indices. While the expert team evaluated potential costs, a team of mission planners and technologists computed anticipated mission costs numerically directly from the mission cost indices. This was based on correlation of the costs indices with historical mission costs to obtain a dollar per cost index multiplier.

5. The estimates were compared. Once the two estimates had been calculated independently, they were compared. Differences between the estimates were evaluated and the reasons behind them were explored. The deeper understanding of the costs incurred allowed for a more complete picture of the required mission funding profile.

6. The best estimate and uncertainty were determined. Once the mission estimates had been compared, a final best estimate was determined. This estimate was based on the two estimates computed and the reasoning behind each estimate, as well as the degree and sources of uncertainty.

7. Mission class was specified. Based on the estimated mission costs, the mission was then classified according to the category of cost profiles in which it belonged. Mission classes are organized in terms of cost ranges, with different classes having different flight frequencies. These classes were characterized as Discovery, New Frontiers, and Flagship.

3. Cost Drivers

To develop an estimate of the costs of a mission, the first step is the identification of mission cost drivers. Cost drivers are the capabilities that the mission requires to complete its objectives. The rapid cost assessment made use of three primary cost driver categories: launch operations, flight systems, and mission operations; four additional categories were also taken into account: environment, technology, heritage, and feed-forward. These categories served to divide the mission into distinct, non-overlapping and covering cost regions, thus ensuring that as many costs as possible were taken into account while eliminating the possibility of double counting.

Launch operations incorporates the costs associated with the mission launch. It is divided into three main subcategories: launch vehicle, launch approval, and planetary protection measures. Different size payloads require different size launch vehicles, and the launch vehicle driver covers the cost of the vehicle used. Launch approval accounts for the amount of resources needed to obtain launch approval, which can change depending on the design of the mission. For example, missions containing radioisotope power systems require more resources to obtain flight approval than missions using other types of power systems. Finally, planetary protection measures account for the amount that must be spent ensuring the spacecraft does not contaminate any potential pre-biotic or biologically active environment and does not contaminate the Earth with a returned sample.

"Flight systems" is the most extensive category of all the cost drivers. Included in this category are all capabilities required in the design of the mission flight and in situ exploration elements, including: cruise stage, orbiter, entry and descent systems, science payload, etc. A detailed list of all current flight system capabilities and corresponding rankings in complexity can be found in Table 1. A recent addition to the flight system was made to account for missions with multiple identical landed elements for network missions.

Mission operations accounts for the costs a mission incurs during operation. These include the lifetime, complexity, and science operations costs of the mission. Typically, the farther the target body of a mission, the longer the mission operational lifetime, and the more resources have to be dedicated to maintaining its operations. Missions with high operational complexities require more dedicated resources once science operations begin, and also have higher operational costs. Likewise, the more complex the operations associated with the return of the science data, the more resources will also have to be dedicated during the operational period of the mission.

Environment accounts for the costs that different types of environments impose upon the mission. Special considerations and designs must be made in order to ensure the mission will operate properly in extreme environments. There exist four typical extreme environments which are explicitly taken into account: high temperature, low temperature, high pressure, and high radiation; however, there also exists a category for other atypical environment costs, which currently is only used for environments categorized as dusty (such as the surface of a comet) or where large number of particulates may be experienced.

The Technology categories account for any technologies that have yet to be developed that the mission requires. Technology is further divided into four subcategories: space systems, autonomy, in situ and sample return, and science sensors. While each of these technology taxonomies represents a different branch of technological development, the amount by which they will drive the cost is determined by similar criteria across all four subcategories. Specifically, the greater the level of technological development which must take place within a subcategory before the mission can be flown, the more that technology need will increase the cost of the mission.

Finally, heritage and feed-forward serve as special types of cost drivers. These do not have any subcategories, but rather, are included within technology. If the mission design requires capabilities sufficiently similar to those of earlier missions, then a heritage cost driver with a negative magnitude can be included to represent the decreased costs associated with inherited validated technologies. If a mission plans to flight validate technologies that are not required for the mission, and thus not accounted for in the capability cost drivers, then a feed-forward cost driver can be included with a positive magnitude to incorporate the added cost.

These cost drivers are meant to capture the costs common to most missions. Not all cost drivers will be present in every mission, in fact it is highly unlikely that one mission will contain every cost driver. Similarly, cost drivers do not capture a totally complete picture of every mission, but rather give a rough idea of the costs involved in a mission. The purpose of the cost drivers are to neatly categorize the sources of mission costs and thus make it possible to estimate the total cost of the mission without expending the resources of conducting a highly detailed study.

4. Cost Driver Indices

Associated with each cost driver is a cost driver index. The cost driver index is a proxy for the overall magnitude of the cost of a certain cost driver within the total mission cost. Cost driver indices are assigned on a five level, exponential scale as follows:

- Level 1 2 Points
- Level 2 4 Points
- Level 3 8 Points
- Level 4 16 Points
- Level 5 32 Points

Levels are assigned based on the complexity of the capability with which they are associated. The more complex the capability a cost driver represents, the higher the value of the cost driver index associated with that driver. The higher the value of the cost driver index, the more expensive that driver will be to the total mission. The number of points assigned to each index represents the total

Table 1 - Description of different cost drivers and the capabilities associated with each cost index level. (continued in Table 2)

Cost Drivers/ Complexity Index	Level 1 (2)	Level 2 (4)	Level 3 (8)	Level 4 (16)	Level 5 (32)
Launch Vehicle					
Main Stage	Delta II with small fairing (2m) (could be too small for SSE)	Delta II with smaller fairing (3m)	Delta IV M or Atlas V with smaller fairing (4 - 5m)	Heavy launch vehicles: Delta IV-H or Atlas V with large fairing (5m)	Multiple Delta IV-H or Atlas V launches with in-orbit assembly
Launch approval		Launch approval for RTGs	Launch approval for RTG's and Earth Flyby		
Planetary Protection	Orbiter mission no new technology	Lander mission no new technology	Landed mission without RPS to Europa or special region on Mars	Landed mission with RPS or Europa or special region on Mars	Sample Return Mission from Europa
Flight systems					
Cruise Stage	Solar cruise stage inner planets	Solar cruise stage- to 5AU (LILT) - or - multiple probe carrier	Cruise stage to outer planet (>5AU) - or - RPS inside aeroshell		
Orbiter		Chemical propulsion	Chemical propulsion + Aerocapture (at Titan, Mars) or SEP	Orbit insertion at multiple satelites or large moons	Orbit insertion with aerocapture at Neptune
Entry or aeroassist system		Small probes to terrestrial planets	Large probes to Mars, Venus, Titan	Large probes to Outer Planets (Jupiter etc.)	Aeromaneuvering during entry OR outer planet probe
Descent and Landing		Dense atmosphere (Venus or Titan)	Airless body (Moon, Mercury, Europa) or balloon deployment near surface	Large lander with thin atmosphere or Outer Planets deep probes	
Planetary Mobility		Free flying aerobot (balloon)	Altitude control balloon or MER class rover	MSL class rover or fully controllable blimp	MSL class rover or blimp on Venus
Ascent vehicle - to upper atmosphere				From surface to 0.1 bar on Titan	From surface to 0.1 bar on Venus
Ascent vehicle- to orbit	Low g no atmosphere (moon), or asteroid	Moderate g - no atmosphere	Moderate g atmosphere (Titan and Mars)	Moderate g with "break-the-chain" PP	Venus atmosphere (i.e., Earth like high g)
Rendezvous - capture			Artificial object - sample return canister	Natural object - asteroid or quiescent comet	Natural object - active comet
Earth Return Vehicle		No environmental control (Genesis or	Maintain cryogenic temperatures	Back Planetary Protection	
Science Payload	Simple - single instrument	Limited or 1 to 20 cm depth sampling	Moderate - 4 to 6 instrument or up to 2 m depth sampling	6 to 10 instrument or up to 100m depth sampling	Remote and in situ instruments or deep sampling (up to km)
Complexity (note: not duplicate units like 2 MERs)	One flight element	two flight elements	three filigh systems	four flight systems	five or more flight systems

Table 2 - Description of different cost drivers and the capabilities associated with each cost index level. (continued from Table 1)

Cost Drivers/ Complexity Index	Level 1 (2)	Level 2 (4)	Level 3 (8)	Level 4 (16)	Level 5 (32)
Operations					
Lifetime	weeks (e.g to Moon)	< 1 year - or - <1 week in Ext. Env	1 to 5 years - or - <6 months in Ext. Env	> 5 years - or - <1 year in Ext. Env	> 18 years (e.g. to KBO)- or - >1 year in Ext. Env
Science	PI led minimal science	Directed mission	Complex science operations		
Operations Complexity		Moderate	High	Extreme and/or novel	
Severe Environments					
Temperature	Low temperatures in vacuum	High temps in vacuum (Solar Probe) or low temps in atmosphere (Titan)	High Temps in atmosphere (Venus) or long duration at high temp vacuum (on Mercury)	High temps in atmopshere with long duration (on Venus)	
Pressure			Venus surface or Outer Planets Deep Probes (90-100 bar)	Extreme high pressure (Jupiter Deep Probes to 1000 bar)	
Radiation	< 0.6 AU or Jupiter Gravity Assist / flyby (10s of kRad)	Long duration missioon or planetary magnetic field encounter (few 100 kRad)	Multiple passes through magnetic field (up to 500kRad to several MRad, e.g. Galileo)	Long duration operations inside magnetic field (10s of MRad, e.g , JIMO)	Long duration surface mission on Europa (multi-10s of MRad)
Other		far range (> 1km) comet dust particles, Mars surface dust	close range comet dust (<1 km), ring particles		
Technology					
Space System	Existing technology only & flight heritage	All technologies at TRL 6 but limited flight	One major mid TRL technologies	One major low TRL system	Several low TRL systems
In Situ and Sample Return Systems	Existing technology only & flight heritage	All technologies at TRL 6 but limited flight	One major mid TRL technologies	One major low TRL system	Several low TRL systems
Sensors and Instruments	Existing technology only & flight heritage	All technologies at TRL 6 but limited flight	One major mid TRL technologies	One major low TRL system	Several low TRL systems
Autonomy	Existing technology only & flight heritage	All technologies at TRL 6 but limited flight	Limited autonomoy but enabling	Sophisticated autonomy is enhancning	Sophisticated auronomy is enabling
Heritage	Nominally zero. Include an estimate as a NEGATIVE number if there is important heritage from prior mission				
Feedforward	Nominally zero. Include an estimate as a POSTIIVE number if mission incorporates features required for subsequent missions				

amount that the cost driver with that index is expected to increase mission costs. For example, when dealing with radiation in the environments cost driver, a mission such as a Jupiter gravity assist/flyby will need minimal protection from radiation (10s of kRad), and thus only a minimal amount of resources will be required to sufficiently prepare the mission, earning it a Level 1 designation. A mission designed for extended operations on the surface of Europa, however, will require significant protection from radiation (many 10s of mRads), and thus it will require far more resources to prepare, earning it a Level 5 designation. A summary of different cost drivers and attributes associated with different indices is provided in Tables 1 & 2.

Once a cost driver index has been assigned to each cost driver, all cost driver index point values for the mission are summed with equal weight. This sum is the mission cost index. Based on this index, an estimate of the mission cost is determined through a directly proportional relationship. Comparison of completed missions to their mission cost index yields a proportion of approximately $14.4 million per point (See Figure 2). It is this mission cost estimate that is then compared to the expert estimate based on the Standard Project Work Breakdown Schedule.

5. Cost Estimation by Experts

In addition to the cost estimate generated using the cost driver indices, an expert team generated an estimate based on the mission profile and experiences of the team members. This estimate was both quantitative and qualitative, designed to not only yield a numerical estimate of mission costs but also to evaluate different sources of uncertainty and generate reasonable bounds of certainty.

The expert team was given a briefing outlining mission objectives, desired capabilities, descriptions of the cost drivers and a set of possible mission profiles. Using the information from this briefing, the expert team compiled an estimate of mission costs based on their past experiences with the required mission attributes. Once these costs were evaluated, a method of applying standard wraps (percentages applied to spacecraft development or operational costs) was used to anticipate costs not directly estimated. The wraps determine costs which do not fit into system attributes, such as project management during design and development or management reserves. The wraps and the expert team estimates were then added to determine the estimate of the total mission cost. In addition to providing

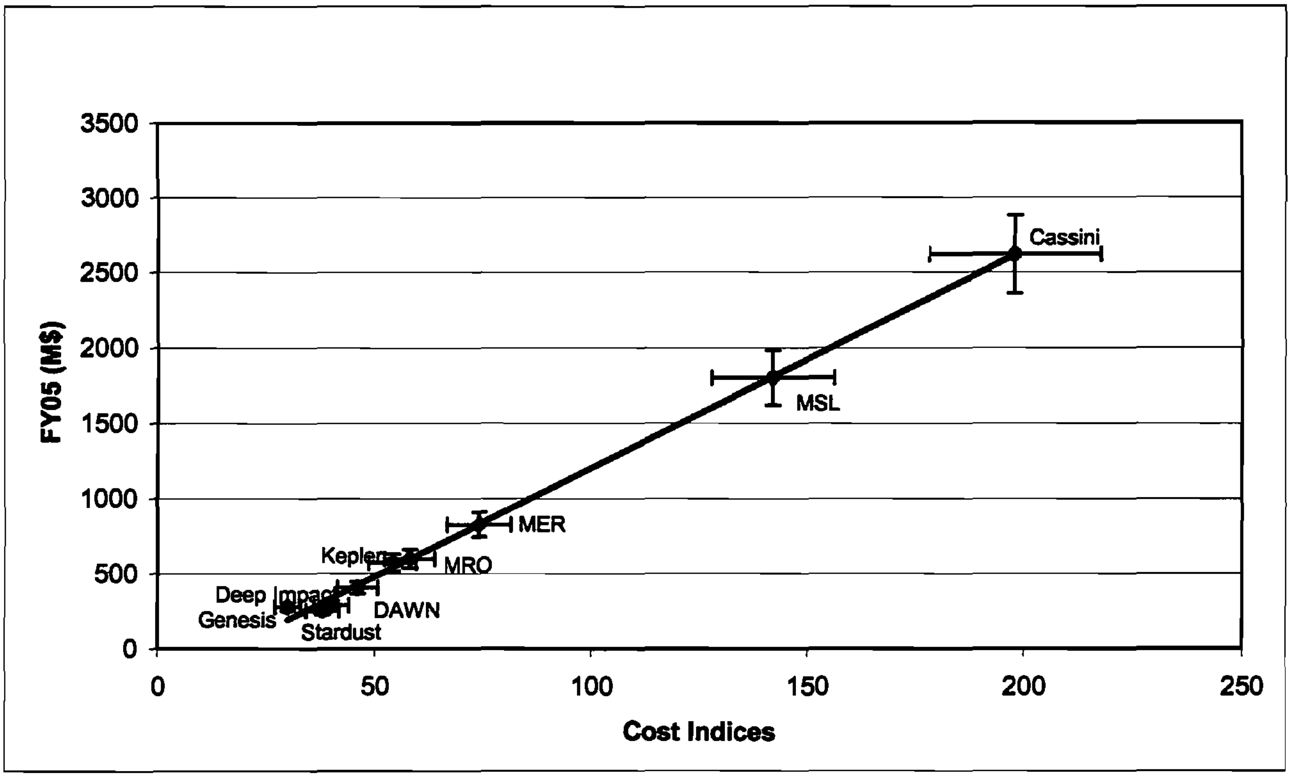

Figure 2 – Comparison of Cost Indices with Historical Mission Cost (with 10% uncertainty)

numerical estimates, the expert team cost analysis included side by side estimates of different mission profiles, as well as descriptions of the sources of uncertainty within the mission profile and the range of uncertainty associated with each mission attribute. Once all of these steps were completed, the expert team cost analysis was compared to the estimate generated by the mission cost indices.

6. COMPARISON AND RESULTS

The rapid cost assessment method was applied to five missions, three Titan missions and two Europa missions, in order to compare the results to those of the expert team. The three Titan missions incorporated different methods of exploring Titan, including an orbiter only mission, in situ balloon only mission, and an orbiter and in situ explorer mission. Likewise, the Europa missions included a mission utilizing an orbiter only as well as an orbiter and lander option. While some factors remained constant for the missions within each set, the variations allowed the application of the rapid cost assessment model to compare different mission options within a set of parameters. When the analysis was completed, it was possible to evaluate not only how well the cost driver indices compared numerically to the expert team estimates but also how well the estimate of cost differences between similar missions generated by the cost drivers compared to those generated by the expert team.

As Figure 3 illustrates, the estimates generated by the mission cost indices were systemically lower than those generated by the expert team. The cost indices generated estimates that were ~10% lower than the expert estimates for lower complexity flagship missions and ~25% lower for high complexity missions. However, because high complexity missions are inherently more difficult to categorize, this result was not unexpected. While the cost indices do make low estimates, they make consistently low estimates, and furthermore, the indices provided a fairly good approximation of the relative differences between mission options.

7. CONCLUSIONS AND FUTURE PLANS

While cost driver indices do not provide a substitute for detailed cost analysis in determining final mission costs, they do provide enough fidelity to be utilized during early planning stages of programs. Cost indices do appear to underestimate costs for missions at the high end of the mission cost range (>$2 billion), however the underestimation appears consistent and thus could be scaled appropriately. The fidelity to relative differences between potential missions also suggests that even at this level, cost indices can be useful. Their ability to rapidly determine an estimate that is both a reasonable approximation of mission costs and of the cost differences between missions can be used to determine initial cost profiles and examine different possible mission sets and possible scheduling profiles. In

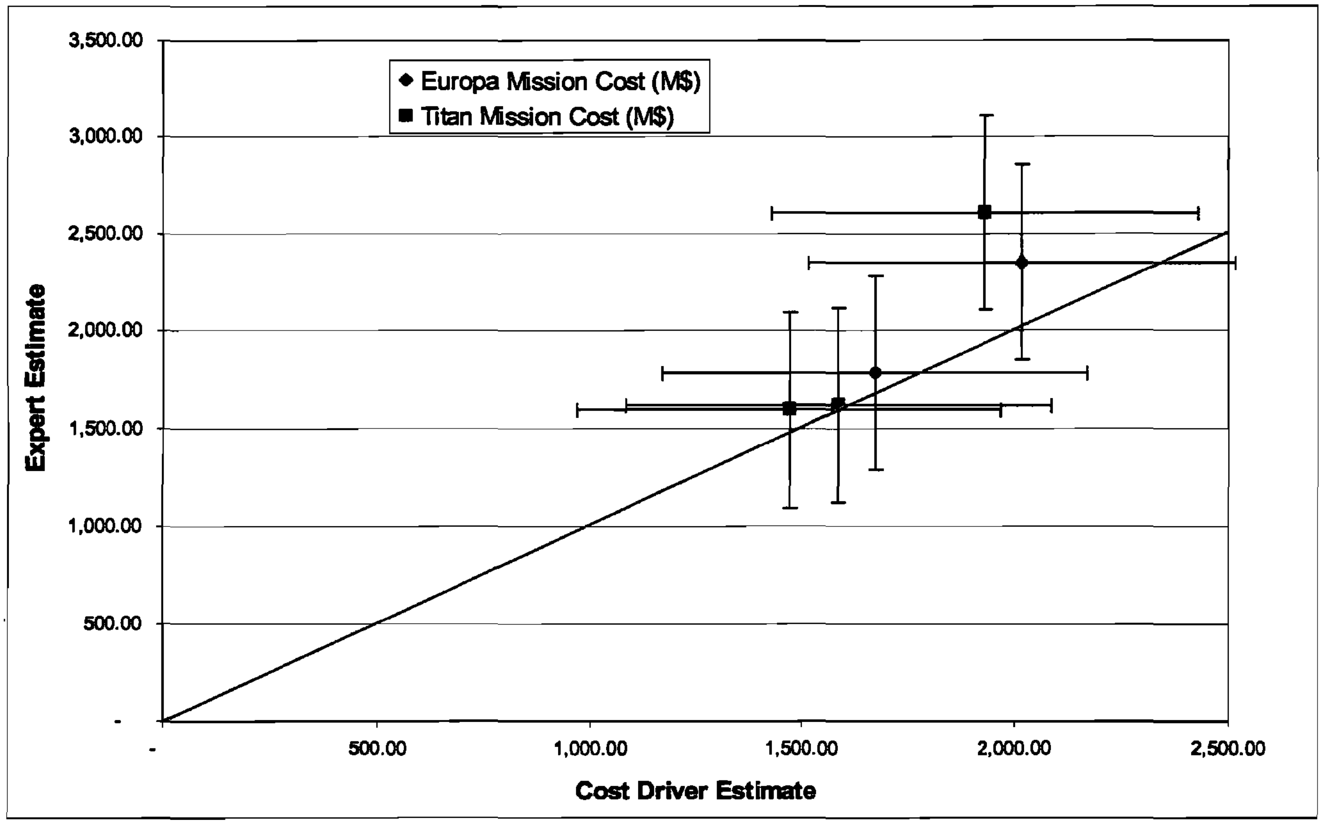

Figure 3 – Comparison of Cost Indices Estimate with Expert Estimate (with 20% uncertainty)

this way, cost driver indices do what they were designed to do.

In order to build confidence in the estimation system, further validation against past missions and future mission studies will prove quite useful. While a fair number of missions were used in the development of cost indices, many more could be used in order to refine the model and assess any additionally needed categories. Furthermore, while the cost indices estimates for Europa and Titan were compared to the estimates of the expert teams, they have yet to be compared to detailed mission cost studies, which could provide deeper insight. In the meantime, mission cost indices provide a powerful tool for relative costing of missions needed for the development of future programs of space exploration. An automated version of the estimation approach is currently being developed that will allow for even more rapid determination of estimates.

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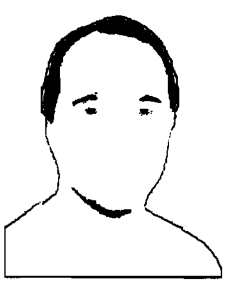
BIOGRAPHY

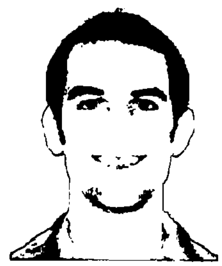
Craig E. Peterson is Technologist for the Jet Propulsion Laboratory's Mission Systems Concepts Section, specializing in evaluating the benefits of potential new technologies for future mission concepts in support of NASA's Space Missions Directorate. He is also the acting director of the Laboratory for Spacecraft and Mission Design (LSMD) at the California Institute of Technology, where he was also a lecturer in the Graduate Aeronautics Program. Peterson holds a BA in Mathematics and Physics from Gustavus Adolphus College and has pursued post-graduate studies in applied mathematics and engineering at UC San Diego, UCLA, and the California Institute of Technology.

James A. Cutts is currently the Solar System Exploration Program Directorate Chief Technologist at JPL. Prior to his present assignment, he was Chief Technologist for the Mars Program Office. During his career at JPL, he has also served as Manager of the Special Projects Office, Program Manager for Advanced Instruments and Space Technology and Deputy Director of the Center for Space Microelectronics. Dr. Cutts participated in the scientific investigation teams for Mariner and Viking investigations of Mars. He has served as Chair of NASA's Sensor Working Group and has been a member of other NASA and U.S. Air Force advisory committees. He holds a BA in Physics from Cambridge University, an MS degree (Geophysics) and Ph.D. (Planetary Science) from Caltech and a Certificate from UCLA's Executive Management Program. He has authored more than 80 papers in space science and technology.

Tibor S. Balint is the Senior Engineer at the Jet Propulsion Laboratory, California Institute of Technology, in Pasadena, CA. His work within the Planetary and Lunar Missions Concepts Group involves programmatic support to NASA's Planetary Science Division, related to Solar System Exploration and to the Nuclear Systems and Technology Office related to RPSs. He also leads Pre-Phase-A mission studies, and specializes in radioisotope power systems. Dr. Balint obtained an MSc degree in mechanical engineering from the Technical University of Budapest, Hungary; an MPhil in chemical engineering from the University of Exeter, UK; a PhD in engineering from the University of Warwick, UK; and an MSc in Master of Space Studies (MSS) from the International Space University, Strasbourg, France. He also worked as a nuclear design engineer for 9 years at Ontario Hydro, Canada, conducting nuclear safety analysis.



James B. Hall is currently studying for an MSc. in Mathematical Modelling and Scientific Computing at Oxford University, UK, where he works within the Oxford Center for Industrial and Applied Mathematics and the Computing Laboratory. He is a member of technical staff at The Aerospace Corporation where he works with the NASA/JPL Advanced Programs organization. Hall has worked for the Systems Modeling and Analysis Group at JPL, and holds a B.S. in Mathematics and Government from Georgetown University.



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