Model-Based Spacecraft and Mission Design for the Evaluation of Technology

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Abstract—In order to meet the future vision of robotic missions, engineers will face intricate mission concepts, new operational approaches, and technologies that have yet to be developed. The concept of smaller, model driven projects helps this transition by including life-cycle cost as part of the decision making process. For example, since planetary exploration missions have cost ceilings and short development periods, heritage flight hardware is utilized. However, conceptual designs that rely solely on heritage technology will result in estimates that may not be truly representative of the actual mission being designed and built. The Laboratory for Spacecraft and Mission Design (LSMD) at the California Institute of Technology is developing integrated concurrent models for mass and cost estimations. The purpose of this project is to quantify the infusion of specific technologies where the data would be useful in guiding technology developments leading up to a mission. This paper introduces the design-to-cost model to determine the implications of various technologies on the spacecraft system in a collaborative engineering environment. In addition, comparisons of the benefits of new or advanced technologies for future deep space missions are examined.

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1. INTRODUCTION

One of the reasons development costs are typically high for robotic planetary exploration is the considerable amount of new technology, hardware and software development improperly applied to the mission. Early in the conceptual design phase there are a number of reoccurring questions to be addressed, one being the pertinent payoffs of various new technologies to the system. Often the acquisition means to advance the state-of-the-art in key technology areas. Advancing or introducing technologies that are required in many cases to achieve program objectives usually increase costs and scheduling risks. Therefore their employment should be kept to a minimum. Consequently, mission requirements can also influence the options of using specific hardware for a mission. For example, mission ΔV requirements, fixed with mass constraints, can limit one to consider only propulsion options having a sufficiently high specific impulse. The desire, then, for maximum performance and minimum mass and volume will require advanced technology and the repackaging of existing subsystems and components to fit the optimized system. So while introducing new technologies without relaxing any other requirements, the implementation demands the application of trade techniques at the system-level to evaluate the design for the mission.

Decisions in characterizing the direct and indirect consequences of new technologies became the focal point during the development of NASA's 2002 Solar System Exploration Technology roadmap. A key issue for the mission designers and technology planners was to quantify the partials with respect to technology for various missions [1]. At the time, no tools or capability existed to address this issue. Since there exists a strong correlation between mass and size of a spacecraft to mission costs, increasing levels of miniaturization of technology have been proposed for New Frontiers Class missions in order to reduce the launch costs. It is also a key indicator of improved performance due to the reduction in subsystem mass. Although managers are influenced to use off-the-shelf hardware with proven flight heritage, it is necessary to consider the application of newer technologies for success of low-cost, fast-pace missions. Thus, the quantitative analysis on how specific technology choices affect a mission at the system-level becomes essential.

The Laboratory for Spacecraft and Mission Design (LSMD) at the California Institute of Technology has developed a reduced order trades tool—Cost and Mass Evaluation of Technology (CoMET) that allows the effects of technology improvements to be calculated for a given baseline mission. CoMET is used to determine the benefits of various assumed technology improvements with the capability to conduct comprehensive trade studies. This paper introduces the collaborative design environment for which CoMET is implemented. It also observes how the methodology of the tool works through an example. In addition, the new capabilities are examined and instances are given where rules of thumb, historical analysis, and professional judgments are used. This paper concludes with a detailed illustration of the design-to-cost model for a future deep space mission and possible paths for the future.

2. Cost and Mass Estimation Environment

Since interplanetary missions are typically higher costing, engineers require an unbiased item-to-item comparison of subsystem components to determine the benefits of technologies for a deep space mission. Engineers at the Jet Propulsion Laboratory (JPL) require tools to analyze the impact of mass and cost savings on a subsystem, the overall vehicle, and the mission itself. Because of associated increases in production complexity, simplified semi-analytical and empirical models for mass and cost are instead used for first-order approximation of all major spacecraft subsystems. These models are based on well established rules of thumb, historical analysis, and engineering judgment. The "design center" environment is modeled after JPL's Advanced Projects Design Center for smaller, cost-driven studies that are designed in considerably less time than in the past. This type of environment can increase productive time via collaborative product workbooks, concurrent engineering methods, and a design-to-cost model, that features the life-cycle as a direct part of each implementation decision. In addition, this design setting addresses the above issues in a methodical, quantitative, and high accuracy manner with a variety of models and tools, including parametric cost models, subsystem mass estimation worksheets, and system-level parameter worksheets.

Further, the approach to constructing such a design-to-cost model focuses on the system-level parameters of interest to the project and considers life-cycle cost and technology effectiveness. At the component level, the mission examines components inherited or extrapolated for predicted technology advances. It allows for faster iterations on design concepts where it speeds up the decision-making process as illustrated in Figure 1.

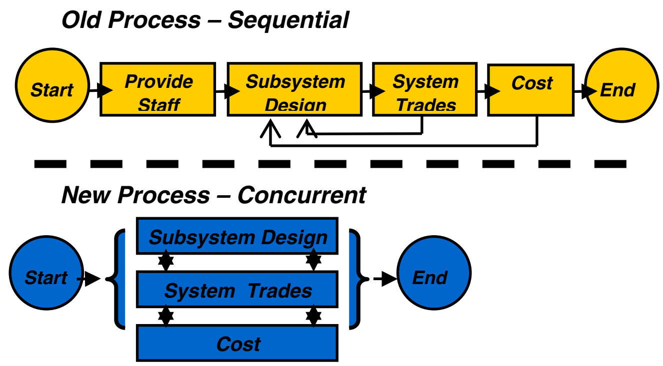

Figure 1 – Concurrent engineering environment

3. Current Project Configuration

The CoMET tool is a parametric model based on two types of parameters: technology-independent called mission parameters such as ΔV or temperature, and technology parameters, such as mass fractions for structural or thermal materials, or specific mass as a function of technology performance (e.g., kilograms/Watt). The technology and mission parameters together comprise the key programmatic parameters for the mission.

The tool primarily uses less than 200 internal design parameters that are maintained in five main Microsoft Excel® workbooks: Mission Selection, Mother, Carrier, Daughter, and the Cost Model linked together through Microsoft Access®. The Carrier and Daughter workbooks export mass requirements to the Mother workbook, where it contains an overall project overview. The Mission Selection worksheet stores the missions being studied and sends mission parameters to the other workbooks. During a design study parameter values are sent from the Mission Selection workbook to the Mother, Carrier and Daughter workbooks. At the end of the study, the Mother, Carrier, and Daughters workbooks send values to the Cost Model, which calculates the mission costs. This process is illustrated in Figure 2. The tool is able to calculate the final mass sensitivity first at the subsystem level, then at the spacecraft level and finally at the project level [2].

This architecture makes it easy to add components, reconfigure the spacecraft, or change mission profiles without affecting the underlying structure. The following sections describe the architecture of the tool built for missions consisting of a carrier, a Mother (orbiter), and a Daughter (probe, lander, etc).

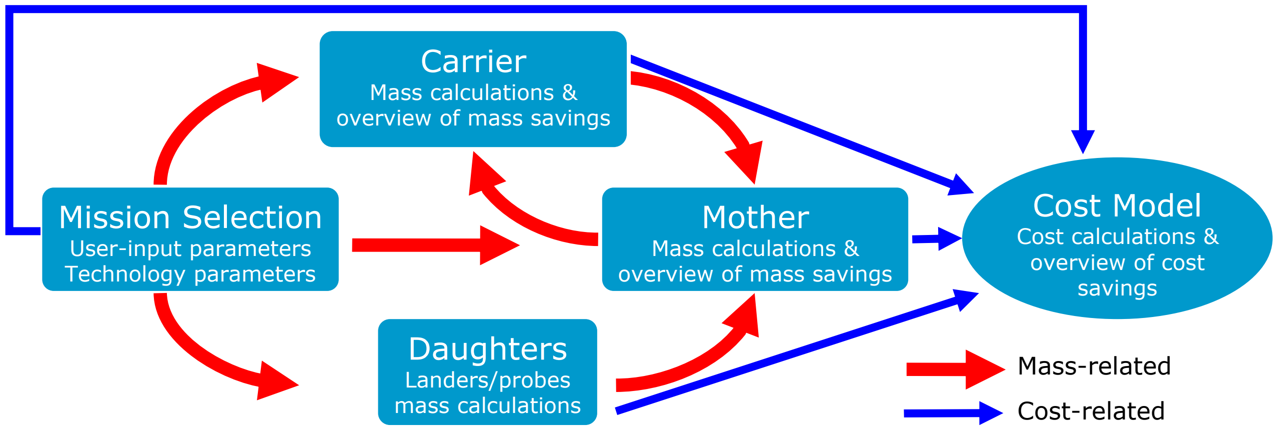

Figure 2 – Cost and mass evaluation tool architecture

Mission Selection

This workbook receives all the inputs from the user that define the scope and broad goals of the mission. The set of mission parameters and technology parameters used to define a study summary are referred to as a Mission Profile. New mission profiles are created in the Mission Selection workbook, and changes to old profiles can be made here. The Mission Selection workbook maintains an overview page for each mission profile studied to date, which stores the mission and technology parameter values used in that study. No changes are made directly to this sheet during the course of the analysis. This provides the ability to roll-back and restart the analysis from a known starting point

The Carrier Workbook

The Carrier workbook represents a propulsive stage of the spacecraft. For example if there is a large chemical propulsion stage that is discarded upon arrival to orbit, it would be modeled in the Carrier workbook. However, the propulsion system would be modeled in the Mother workbook if the propulsion system were kept onboard the spacecraft. Since not all missions have a Carrier stage, this part of the tool can be "switched off." When a Carrier stage is used, it receives a combined Mother/Daughters mass (*i.e.*, the mass the propulsion stage must exert) from the Mother workbook, calculates the mass of the Carrier stage, then sends this mass back to the Mother workbook.

The Mother Workbook

This workbook characterizes the orbiter portion of the space mission, or the entire spacecraft in case of a non-orbiting mission. Often this includes any propulsive system used to place the spacecraft in its mission orbit, with the exception of a carrier stage. The masses of the mother are calculated from combinations of the technology and mission parameters. For example, a mission requirement of 20 GB of data storage is needed where technology state-of-the-art allows 0.5 kg/GB. The data storage will then have a mass of 10 kg. A project overview of the spacecraft mass is maintained in the Mother workbook with total and percent-of-total mass savings for the state-of-the-art, Team X calculations, and advanced values.

Table 1. List of Spreadsheets for Carrier/Mother

- Main Sheet
- Inputs
- Outputs
- Overview
- Setup
- ADACS
- C&DH
- Structures
- Power
- Propulsion: Chemical (Primary)
- Propulsion: Electric (Primary)
- Propulsion: Chemical, ADACS
- Telecom
- Thermal
- Cost
- Constants
- Variables
- Pulldowns

The Daughter Workbook

This workbook is characterized by any de-orbited portion of the mission for planetary entry such as landers, atmospheric probes, etc. More sophisticated than the Mother and Cairrer workbooks, the Daughter workbook uses a considerable amount of mission parameters and user-inputs to estimate the mass and power requirements of the probe. Current developments of the workbook include aeroshell analysis, descent and landing systems and the addition of inflatable aerial vehicles such as blimps or balloons. Because the Mother workbook only sees the mass and power requirements from the Daughter workbook, changes in modeling could easily be made without necessitating a redesign of the rest of the tool. The Daughter improvements will be described in more detail in the Section 5.

Cost Model Workbook

The Cost Model Workbook receives mass estimates from the Mother, Carrier, and Daughter workbooks, and computes cost estimates for both the state-of-the-art and advanced values, based on the JPL parametric cost model (PMCM). These estimates are broken down by spacecraft, so that separate costs are computed for the mother, carrier, and daughter crafts. Each of the separate spacecraft costs are also broken down by subsystem in order to compare cost savings by subsystem. Costs that are specific to the mission, such as project management costs, are also calculated and added to the total cost. The total and percent cost savings for the state-of-the-art and advanced values are sent to the Study Summary. The newest feature of the Cost Model involves the ability to display the mass reduction required to switch to a smaller launch vehicle, along with the savings in cost that would be gained based. The goal of this feature is to reveal situations where a small reduction in mass would result in large savings in cost.

Study Summary

The Study Summary workbook creates a detailed analysis of the mass and cost savings for each parameter. Essentially, it is a semi-automated data record that receives mass savings inputs from the Mother and Carrier workbooks, and cost savings inputs from Cost Model. These savings are calculated in terms of both percentage and total. This sensitivity analysis determines which technological areas would benefit the most from development and improved spacecraft performance.

4. COMET OPERATIONAL PARADIGM

Each spacecraft workbook (Carrier, Mother, or Daughter) contains semi-analytical and empirical models for mass and cost that are organized into a set of spreadsheets, one for each spacecraft subsystem. The mass and power requirements for each of the subsystems in the spacecraft are calculated based on the mission selected and the technology performance parameters. The sum of the power usage of all the subsystems is required to size the power subsystem, while the sum of the subsystem masses are used in turn, to size the amount of structural mass and propellant mass required to add in order to obtain the spacecraft wet and dry masses. Because of the interrelated nature of spacecraft structure and propellant mass, these equations are iterated until the final masses converge to a stable value within a user specified threshold (usually less than 1%.)

If one or more daughter craft exist, their masses are passed back to the Mother where they are treated as additional payload mass for the purposes of calculating the total required Mother mass. If a Carrier is being used, the total Mother mass (including that of the daughters) is treated as payload by the Carrier in order to appropriately calculate the Carrier wet and dry masses. The results of all of these calculations are communicated to the Mother, where it can be viewed as part of an Overview Summary of masses. It should be noted that the tool currently applies a 30% mass contingency to the dry masses, and the total wet mass of the entire system is then compared to the launch mass capability of the specified launch vehicle to determine the launch mass margin.

These calculations are performed three times – first for the baseline values (usually obtained from a JPL Team X or other pre-project study). The results of these calculations is compared to the subsystem masses obtained from the more detailed study and include scaling factors that correct for any difference between the tool calculated value and the baseline study are obtained. The second and third versions calculated represent the State of the Art (SOA) and Advanced technology parameters that are being compared in the analysis. The scaling factors determined in the baseline calculations are applied to mitigate any limitations in the basic equations and maintain conformity with the baseline calculations. These are displayed on the overview sheet along with the baseline values. The mass differences between the SOA and Advance values is also calculated and displayed, both in terms of kilograms, and in terms of percentage of the launch mass.

The mass and savings results are passed to the cost model workbook. The costs are revised and passed to the life-cycle cost accumulation spreadsheet in the cost model. In the cost model, a similar four-column display is used: the first for baseline state-of-the-art implementation, the second for Team X values taking in consideration to a trade study, third for advanced technologies to be developed, and the fourth for differences.

The Microsoft Access® user interface allows a user to specify a technology parameter to change, the range and number of values to calculate, and the desired set of output variables (e.g., percent change in launch mass, Cost savings in millions of dollars, etc.) It then exercises each spacecraft element workbook as required to calculate the changes and then plots them on a graph.

5. New Techniques and Measurements

The new capabilities in CoMET include additional elemental improvements to the Daughter workbook. Since missions to the outer planets require a diverse range of technologies to ensure success [3], the workbook includes entry, descent, and landing systems (EDL) as high in priority. These systems support highly capable suits of in situ instruments for atmospheric probes, landers, or airborne platforms. The methodology for calculating the mass is derived from historical analysis, rules of thumb, and professional advice, which contribute to more accurate mass estimations.

Aerothermal Analysis

During entry into a planet's atmosphere, a planetary probe will experience considerable amounts of convective or radiative heating due to probe velocity and the planet's atmospheric density. To protect against this heating, a planetary probe requires a thermal protection system (TPS). In addition, TPS analysis is also used in part of the following segment for EDL. Therefore estimation of TPS is essential to CoMET. Future missions will require larger EDL masses, higher entry velocities, and non-equatorial landing sites. The challenge, then, will be to necessitate the new trade off analysis between the development, mass, and success for planetary missions. Figure 3 shows an example of historical mass data used to calculate TPS mass fraction of the aeroshell.

Heat rate is calculated as a function of velocity, density and Sutton-Graves constants. Density is calculated through an exponential atmosphere–which possesses less than 5% error. Velocity is calculated through a three degree-of-freedom based on probe's entry velocity, maximum radius, and effective radius; or through Allen-Eggers trajectory profile.

Descent and Landing Systems

For parachutes, the terminal descent equation is derived in a short course by Dr. Juan R. Cruz at NASA Langley.

$$S_O = (\frac{mg}{q} - C_{DEV} S_{EV}) / C_{DO} \qquad (1)$$

This equation represents the nominal surface area (S_o) of a parachute in terminal descent. Where q represents dynamic pressure, C_{DEV} represents coefficient of drag of the entry vehicle, S_{EV} represents cross sectional area of the same vehicle, and C_{DO} represents coefficient of drag of the parachute. The nominal surface area is the area based on canopy constructed surface area and is generally used as the reference area of the parachute. Since this equation is only true for a parachute in terminal descent, it is used to size the drogue parachute if it is included or the main parachute if the drogue parachute is not included. Once the surface area of the parachute is known, there exists a rule of thumb that approximates the mass of the parachute where $m = 0.1055 S_0$.

For propulsive descent, the rocket equation is used to compute propellant usage (ΔV) and find the wet spacecraft mass ratio. A pressure-volume rule of thumb is then used based on the propellant mass (from the ratio) to estimate propellant tank material mass and pressurant masses. Landing systems employ landing legs, crushables or airbags. The required mass of the crushables is determined from mechanics equations to estimate the required mass to withstand the impacting force; however, airbags are derived from a linear relationship

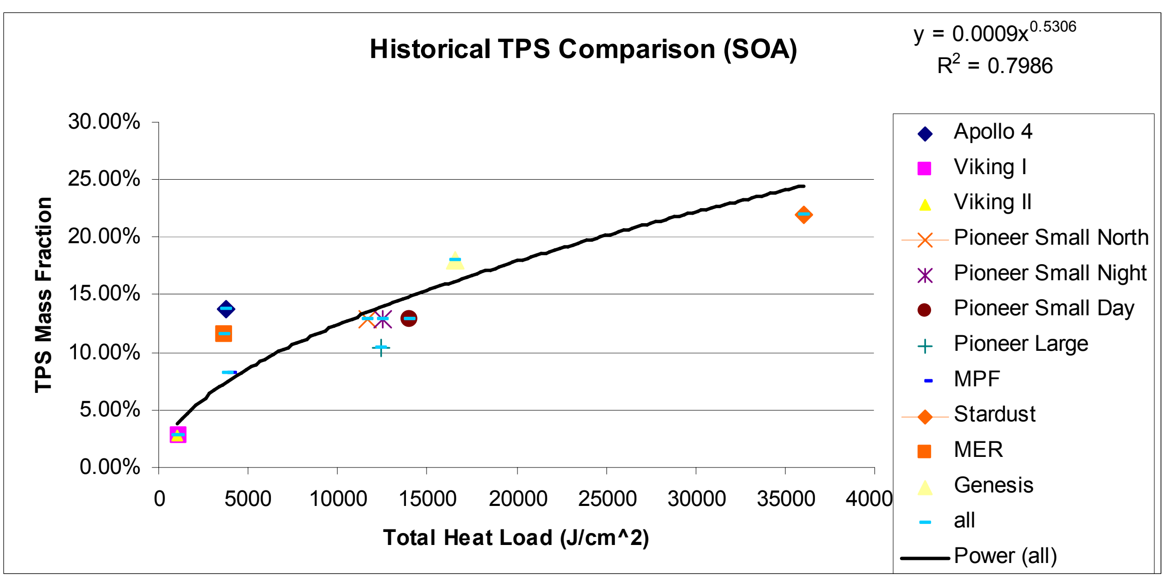

Figure 3 – Historical analysis for TPS mass estimation

Blimps/Balloons

Balloons and blimps are prime candidates for use as probes on planets and moons with an atmosphere, such as Venus, Mars, and Titan. The basic sizing relations are obtained through Archimedes' Principle and the ideal gas law. This requires knowledge of atmospheric conditions where geometric relationships are derived. All calculations are iterative, allowing more capabilities to acknowledge the impacts that "ripple" through from the technology trades.

Launch Vehicle Analysis

Identifying and selecting the launch vehicle and trajectory design takes place during the mission definition phase. Naturally, the launch vehicle greatly contributes to the total mission cost, but also directly affects available hardware options and their associated costs. Since interplanetary missions are long duration missions with extremely high launch costs, reducing costs due to the launch vehicle demand the optimization and minimization of mass. After the C_3, or residual energy, and mass calculations are stored in the database, a launch vehicle can be selected. The relationship between the required C_3 and maximum payload is found for each launch vehicle using exponential fits of launch vehicle performance data from the Kennedy Space Center. Based on the total launch mass calculated from the rest of CoMET, the launch vehicle tool is able to select the launch vehicle which could lift this mass. The tool then calculates how much the total launch mass would need to be reduced to fit on a smaller launch vehicle and shows the cost savings for fitting on a smaller launch vehicle. The launch vehicle costs are based on a cost model for the year 2011, and later years are approximated with a four percent increase per year. Table 2 describes the example for a launch mass of 1189 kg and launch date of 2012 with a C_3 of 27.7 km2/s2 and calculates the potential launcher. Table 3 shows possible cost savings from the Delta IV (4040-12).

Table 2. Cost Estimation Relationship for payload

Launch Vehicle	Cost ($M)	Max Payload (kg)
Delta II **(2325-9.5)**	94.4	333
Delta II (2425-9.5)	96.2	415
Delta II (2925-9.5)	104.4	691
Delta II (2925H-9.5)	115.4	803
Atlas V (501)	145.8	1387
Delta IV (4040-12)	127.7	1209
Atlas V (401)	137.3	1962
Atlas V (511)	149.9	2147
Atlas V (521)	154.1	2660
Delta IV (4450-14)	156.0	2406
Atlas V (531)	158.2	3113
Atlas V (541)	162.2	3524
Atlas V (551)	166.4	3841
Delta IV (4050H-19)	259.6	5511

Table 3. Potential cost savings from launcher baseline

Launch Vehicle	Cost savings ($M)	Mass reduction (kg)
Delta II (2325-9.5)	33.28	856
Delta II (2425-9.5)	31.512	774
Delta II (2925-9.5)	23.296	498
Delta II (2925H-9.5)	12.272	386
Atlas V (501)	0	0
Delta IV (4040-12)	0	0
Atlas V (401)	0	0
Atlas V (511)	0	0
Atlas V (521)	0	0
Delta IV (4450-14)	0	0
Atlas V (531)	0	0
Atlas V (541)	0	0
Atlas V (551)	0	0
Delta IV (4050H-19)	0	0

6. Interplanetary Mission Example

Based on the National Research Council of the National Academies' Decadal Survey *New Frontiers in the Solar System: An Integrated Exploration Strategy*, a second mission to Jupiter is a high science priority for understanding planetary chemistry of gas giants. Using the lessons learned from the Galileo mission in December 1995, this second frontier mission would either explore Jupiter's Polar Regions or delve deeper into the Jupiter atmosphere. The budget cap for a frontier mission is less than $700 million.

Jupiter's atmospheric conditions are extremely unforgiving toward any planetary probe. Pressures can reach up to 100 bars with temperatures ranging from -140 C to 380 C. In fact, the Galileo probe required 50% of its entry mass composed of heat shield material. Note that the Galileo probe entered at 60 km/s on Jupiter's equator and survived up to 21 bars of pressure. Based on the heat shield material employed at the time (carbon-phenolic, which is no longer in production), a polar entry into Jupiter would require nearly 75% of its entry mass composed of heat shield alone. This approximation does not include the thermal control needed to mitigate the radiative effects caused by Jupiter's dense atmospheric molecules releasing energy (and thus heat) when the new probe enters at over 60 km/s.

Furthermore, Galileo succumbed to Jupiter's high pressures of over 21 bars of pressure after entry; a Jupiter deep entry probe would require a substantial improvement in pressure vessel structure strength and mass efficiency to survive the 100 bars of pressure recommended by the National

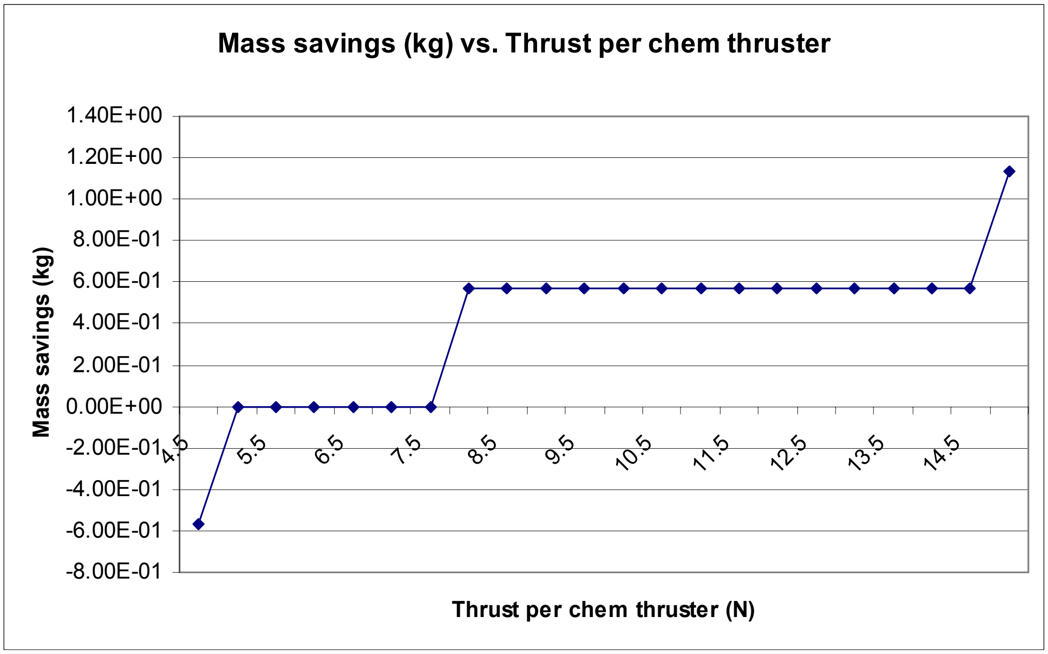

Figure 4 – Example of determining diminishing returns for a chemical thruster on the Jupiter Deep Entry Probe mission.

Research Council's Decadal Survey [4]. Trade studies would include the pressure vessel's primary material constituent and its affects on mass, cost, and performance. For example, a Team X Jupiter Probes study predicted that a pressure vessel composed entirely of titanium would only impose an 18 kg addition to the total system mass, with respect to Galileo heritage [5]. The Titanium monolithic shell configuration also possesses flight heritage from the Pioneer Venus probes. However, Inconel 718 or a Titanium Metal matrix composite would have a lighter weight and stronger performance, albeit a lower TRL and thus higher cost development.

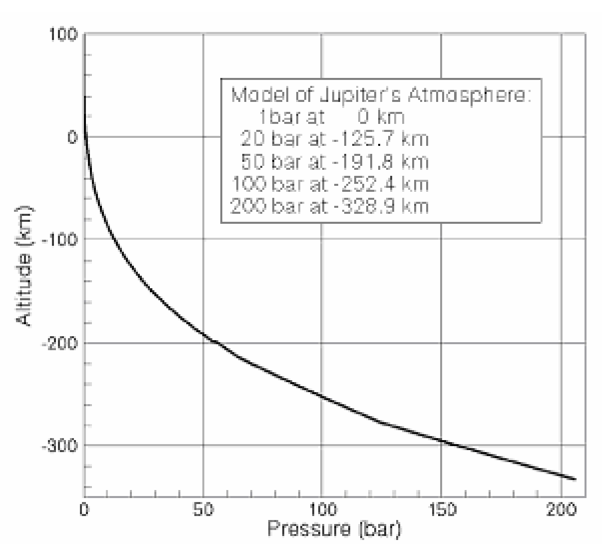

Figure 5 – Pressure difference during probe entry into Jupiter [6].

In addition to the technology improvements in the Daughter workbook for EDL subsystems, technology improvements in Carrier propulsion and power possess high potential for Jupiter probe mass and cost reduction. Electronic propulsion would increase system mass margin; reduce total energy requirements; and ultimately produce cost and mass savings for higher safety margins or wider scientific exploration. Further, commandeering of advanced technologies from other planetary programs, such as Ultralight Composite Overwrapped Pressure Vessels from Mars Exploration Rover heritage would have potential to reduce mass on the Jupiter Deep Entry Probes.

The results of this report will show technology trade-off benefits (and diminishing returns) for a Jupiter deep entry probe mission to the equator or to the Polar Regions. High performance but lower density heat shields such as carbon-carbon would reduce the probe's heavy mass fraction on heat shield. Outlined above, the impetuses behind such technology advancements are due to Jupiter's high temperatures and pressures and due to the long mission duration and distance. The results of this report will hinge on CoMET's analysis of technology advancements to the following systems: Carrier power, Carrier propulsion, Daughter TPS, Daughter power, and Daughter structure.

7. CONCLUSIONS AND FUTURE DIRECTIONS

Introducing new technology and quantifying their implementation can allow for higher performing deep space missions. A key issue for the introduction of new technology is to reduce the mass of and increase instrument usage onboard the spacecraft. However, increasing development of new or advancement technologies requires the application of early system-level techniques for trade studies to ensure the technology is appropriate. Most technologies exhibit a plateau behavior beyond which improvements have negligible benefit to the mission. Understanding when the plateau occurs yields significant fiscal implications. Therefore, a need exists to define the most productive investments in technology development for a mission and to quantitatively compare the benefits with possible alternative choices.

CoMET is a technology evaluation tool designed to specify how technology choices affect a mission at each system level. The mathematical models used in the tool are simplified semi-analytical models for mass of all major subsystems. These models are developed through research into historical analysis, established rules of thumb, and engineering judgments at JPL. CoMET utilizes Microsoft Excel® worksheets for the calculations and uses Microsoft Access® for the user interface and parameter database. One of the identifiable needs is quantifying missions for probes, landers, and airborne platforms.

CoMET is an ongoing project approaching future web-based implementation phase. In addition, development and integration of exploration rovers is expected. Also expected is modeling for sample return missions and models for reducing cruise time. Several different missions from JPL's Team X are expected to be included for studies. The developments of these tools and models are used in key technology areas will yield the greatest benefits to complex robotic missions over the next decade.

8. ACKNOWLEDGEMENTS

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BIOGRAPHIES

Ben S. Bieber *is receiving a double bachelors of science in Mechanical and Electrical Engineering at the University of North Dakota. He has worked several years as an Undergraduate Research Assistant and Teaching Assistant for the Electrical Engineering and Physics Departments, respectively. A 2003 NASA Space Grant Fellow, he has worked on a small satellite project emphasizing data acquisition and remote sensing. Recently he has served as a California Institute of Technology Student-Faculty Program Fellow for the Jet Propulsion Laboratory. His research interests include advanced astrodynamics, mission analysis and design, and satellite systems engineering.*

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Chi Won Ko *is currently a sophomore undergraduate at the California Institute of Technology. He is currently majoring in mechanical engineering, business and economic management and minoring in control dynamic systems. His research interests are broad and include in the disciplines of physics, mechanical engineering, and aerospace engineering.*

Craig Peterson *is Technologist in the Jet Propulsion Laboratory's Mission Concepts Section specializing in evaluating the benefits of potential new technologies for future mission concepts in support of NASA's Space Science Enterprise. He is also the acting director of the Laboratory for Spacecraft and Mission Design (LSMD) at the California Institute of Technology, where he is 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.*

Angela Magee *will receive a Bachelor of Science in Engineering and Applied Science (Concentration in Aeronautical Engineering) from Caltech in June 2006. She worked one summer at JPL on image analysis of weather using programming in Matlab. She worked two summers at Caltech on the CoMET program. She is hoping to go on to graduate school to get a PhD in aeronautical engineering or astronautical engineering.*

APPENDIX

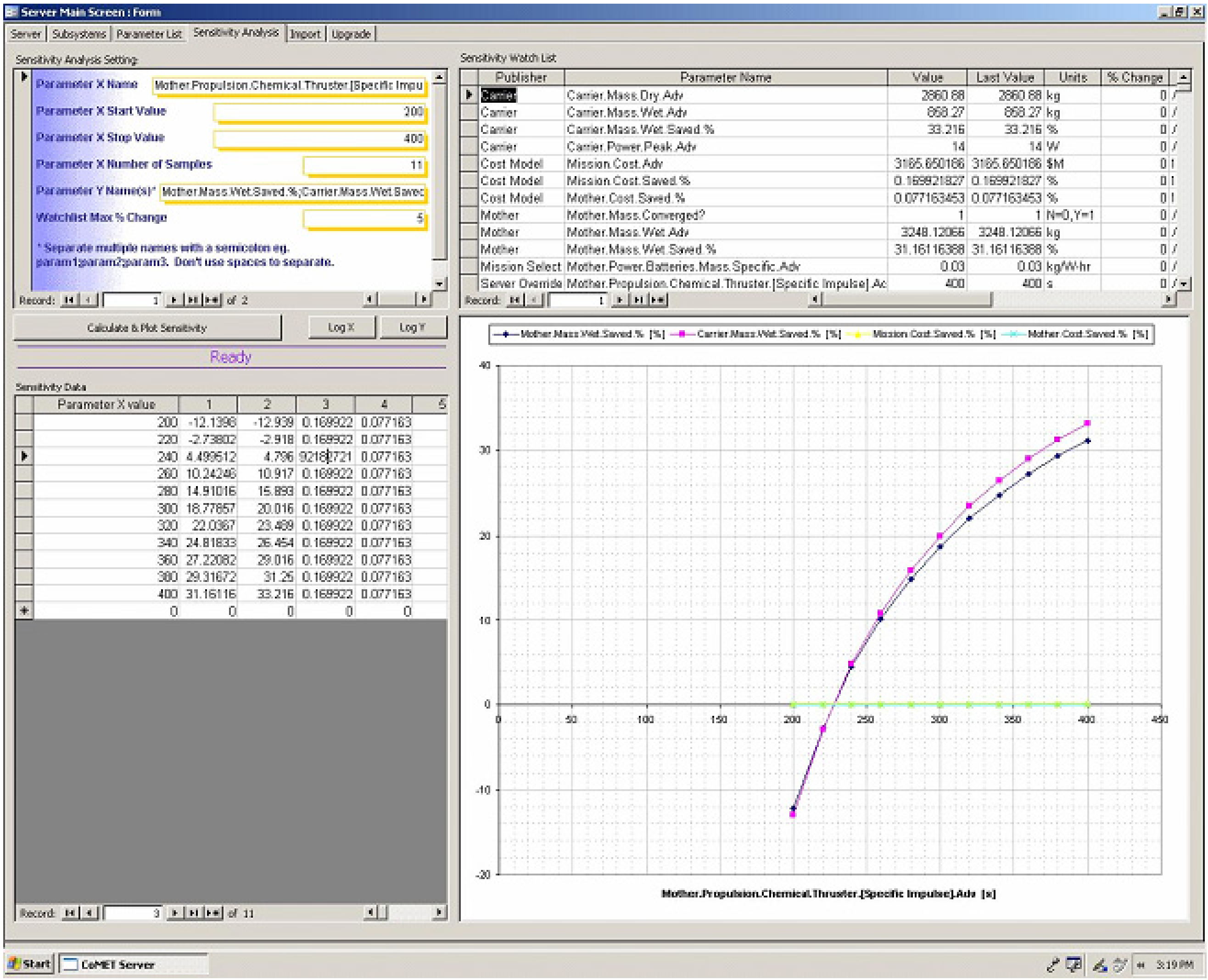

Figure 3 – A demonstration of the quantitative analysis CoMET provides to its users