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Development of Risk Uncertainty Factors from Historical NASA Projects

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DEVELOPMENT OF RISK UNCERTAINTY FACTORS FROM HISTORICAL NASA PROJECTS

by

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ABSTRACT

DEVELOPMENT OF RISK UNCERTAINTY FACTORS FROM HISTORICAL NASA PROJECTS

Tahani R. Amer
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Director: Dr. C. Ariel Pinto

NASA is a good investment of federal funds and strives to provide the best value to the nation. NASA has consistently budgeted to unrealistic cost estimates, which are evident in the cost growth in many of its programs. In this investigation, NASA has been using available uncertainty factors from the Aerospace Corporation, Air Force, and Booz Allen Hamilton to develop projects' risk posture. NASA has no insight into the developmental of these factors and, as demonstrated here, this can lead to unrealistic risks in many NASA Programs and projects (P/p). The primary contribution of this project is the development of NASA missions' uncertainty factors, from actual historical NASA projects, to aid cost-estimating as well as for independent reviews which provide NASA senior management with information and analysis to determine the appropriate decision regarding P/p. In general terms, this research project advances programmatic analysis for NASA projects.

DEDICATION

I would like to thank my family and friends for going the distance with me. To my husband, Mourad, who supports me in my life's accomplishments. To my children, Layla, Nader, Maryam, and Yasmeen, thank you for being my best cheerleaders and bestower of worthiness. To my son, Nader, a special thank you for being my safety net, for showing me that it was possible to finish, for being there for me during the most difficult times, and for graciously excusing me for not making dinner, when I had to "dissertate."

Finally, I dedicate this work to the memory of my father, Reffat Ayoub.

ACKNOWLEDGMENTS

"Seek knowledge wherever it is,"
Prophet Mohamed (PBUH)

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Finally, I have deep appreciation for my two advisors, Dr. Pinto and Dr. Jarvis. Both provided continuous guidance, advice, encouragement, direction, and enlightenment through the whole process of 48 months of hard work between classes, research, NASA workload, my daughter's wedding, my son's hospitalization, and Egypt's revolution.

NOMENCLATURE

μ	Continuous Parameter
σ	Continuous Parameter α > 0
γ	Continuous Location
APRAM	Advanced Programmatic Risk Analysis and Management
BAH	Booz Allen Hamilton
BOE	Basis Of Estimate
CA	Convening Authority
CADRe	Cost Analysis Data Requirement
CDF	Cumulative Distribution Function
CDR	Critical Design Review
CEH	Cost Estimating Handbook
CER	Cost Estimating Relationship
CG	Cost Growth
CL	Confidence Level
CLT	Central Limit Theorem
CPA	Critical Path Analysis
CPI	Cost Performance Index
CRL	Cost Readiness Level
CRM	Continuous Risk Management
DCAA	Defense Contract Audit Agency
DOD	Department of Defense
DOE	Department of Energy

DOI	Department of Interior
DRD	Data Requirements Description
EAG	Evaluation and Assessment Group
EDIFACT	Electronic Data Interchange for Administration, Commerce and Transport
EROS	Earth Resources Observation and Science
ETC	Estimate-to-Complete
EVM	Earned Value Management
EVMS	Earned Value Management System
FAA	Federal Aviation Administration
FOT	Flight Operations Team
FUSE	Far Ultraviolet Spectroscopic Explorer
GAO	Government Accountability Office
GPM	Global Precipitation Measurement
GSFC	Goddard Space Flight Center
HQ	Headquarters (NASA)
I&T	Integration and Testing
ICE	Independent Cost Estimate
ILCR	Independent Life-Cycle Reviews
IMS	Integrated Master Schedule
IPAO	Independent Program Assessment Office
JCL-PC	Joint Confident Level- Probabilistic Calculator
JWST	James Webb Space Telescope
KDP	Key Decision Point

KEPP	Key Engineering Performance Parameters
LCCE	Life-Cycle Cost Estimate
LDCM	Landsat Data Continuity Mission
LRE	Latest Revised Estimate
LRO	Lunar Reconnaissance Orbiter
MDR	Mission Definition Review
MLE	Maximum Likelihood Estimation
MMS	Magnetospheric MultiScale
MOC	Mission Operations Center
MOE	Mission Operations Element
MOM	Method of Moments
MSL	Mars Science Laboratory
NASA	National Aeronautics and Space Administration
NID	NASA Interim Directive
NIH	National Institutes of Health
NPD	NASA Policy Directive
NPR	NASA Procedural Requirement
NSTC	National Science and Technology Council
NUF	NASA uncertainty factor
OCE	Office of Chief Engineer
OCO	Orbiting Carbon Observatory
OLI	Operational Land Imager
OMB	Office of Management & Budget

P/p	Program and project
PDF	Probable Density Function
PMB	Performance Measurement Baseline
P-P	Probability-Probability
Q-Q	Quantile-Quantile
QTIPS	Quantitative Techniques Incorporating Phasing and Schedule
RBSP	Radiation Belt Storm Probe
SCI	Schedule/Cost Index
SDO	Solar Dynamics Observatory
SEE	Standard Error of the Estimate
SMD	Science Mission Directorate
SPI	Schedule Performance Index
SRB	Standing Review Board
SRR	System Requirements Review
TIRS	Thermal Infrared Sensor
TRL	Technology Readiness Levels
UFE	Unallocated Future Expense
USGS	U.S. Geological Survey
VAFB	Vandenberg Air Force Base
WBS	Work Breakdown Structure
WIRE	Wide-field Infrared Explorer
WISE	Wide-Field Infrared Survey Explorer

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CHAPTER 1

INTRODUCTION

"All things are difficult before they are easy."
- Thomas Fuller

1.1 Background

NASA's Space Flight Programs and projects (P/p) are considered highly visible national assets and priorities. The Agency's strategic plan articulates these space flight goals and the timetable for reaching them. P/p management translates the strategy into the actions needed to achieve these goals. Thus, NASA defines the requirements for effective P/p management to fulfill its mandate and commitments. From NASA's perspective, there is a distinction between the Program and project. Program is a strategic investment that has a defined architecture, technical approach, requirements, funding level, and management structure that initiate and direct one or more projects. A Project is a specific investment identified in a program plan and has defined requirements, a life-cycle cost, a beginning, and an end. A project yields new or revised products that directly address NASA's strategic needs.

The purpose of the independent life-cycle reviews (ILCR) of P/p is to ensure mission success. These formal reviews, with selected team members, provide an independent assessment of emerging designs against plans, processes, and requirements to ensure an objective assessment of the design and development plans. By having independent experts conduct these reviews, the review team provides a unique view that a P/p may have overlooked as a consequence of their close involvement with the ongoing P/p work. A major P/p goes through an ILCR, which is the analysis of a proposed P/p by an independent team composed of management, technical, and programmatic experts from outside the P/p management authority. It provides NASA management with an independent assessment of the readiness of the P/p to proceed. There are three objectives for conducting ILCRs:

1. The Agency wants the P/p to receive independent assurance that they will achieve mission success.
2. The NASA senior management, associate administrators, center directors, and the NASA Chief Engineer all need to understand that the P/p is meeting its commitments, is performing according to plan, and that externally impediments are addressed. By conducting ILCR, senior management gains understanding of the P/p status and can make informative decisions relative to the P/p.
3. NASA needs to provide its external stakeholders, such as the Office of Management & Budget (OMB), Congress, and policy makers, the assurance that NASA is meeting its commitment. Its external stakeholders require reviews at major milestones to ensure sufficient management involvement in the decision process prior to continuing into the next phase. The intent of ILCRs imposed on P/p is to ensure mission success. The Standing Review Board (SRB) is an advisory body and can provide recommendations during the key decision points (KDPs) within the P/p life-cycle.

The NASA Convening Authority (CA), which is composed of associate administrators, center directors, and the NASA Chief Engineer, reviews these recommendations and makes one of the following decisions based on the results of the ILCR:

a. Confirm the P/p to the next phase-continue

b. De-scope P/p requirements and objectives

c. Cancel the P/p

d. Provide more resources to the P/p to meet requirements

1.2 Details of the Independent Life-Cycle Review

A significant additional benefit to the P/p is that preparation for the milestone review requires the P/p managers and team to examine holistic progress against specific criteria for each milestone. This permits both the development team and the independent review team to see how well the work is progressing and to examine the assumptions and analyses that support the conclusion the P/p has reached regarding its maturity and readiness to proceed.

The depth of the independent review is to the extent at which the review board can determine that the entire design holds together adequately, and that the analyses, development work, systems engineering and programmatic (e.g., cost, schedule, etc.) support the design and the decisions that were made. Typically, this requires evaluation of the work at the system level. Additionally, the independent review function is identifying cost, schedule, and technical performance risks as well as identifies the consequences of P/p success.

The independent P/p reviews usually examine the following six criteria for P/p:

1. Alignment with NASA Goals
2. Management Adequacy
3. Technical Adequacy
4. Integrated Cost and Schedule Adequacy
5. Resource Adequacy

6. Risk Management Adequacy

As part of the independent review, focus is on the risk assessment of the P/p. Risk is the pressures to meet cost, schedule, and technical performance which are the practical realities in engineering today's systems [Haimes, 2004]. Risk is defined, if it occurs, as the combination of the probability that a P/p will experience an undesirable event and the consequences, impact, or severity of the undesired event. The undesirable event may come from technical or programmatic sources (e.g., a cost overrun, schedule slippage, safety mishap, health problem, malicious activities, environmental impact failure to achieve a needed scientific or technological objective, or success criterion.) The technical and programmatic sources are interdependent and interrelated, thus one cannot separate theses sources. Managing risk is managing the inherent contention that exists within and across all these dimensions. Both the probability and consequences may have associated uncertainties. Risk assessment (see Figure 1) is an evaluation of a risk item that determines (Haimes, 2004):

1. What can go wrong?
2. How likely is it to occur?
3. What are the consequences?
4. What are the uncertainties associated with the likelihood and consequences?
5. What are the trade-offs?
6. What are the future impacts?

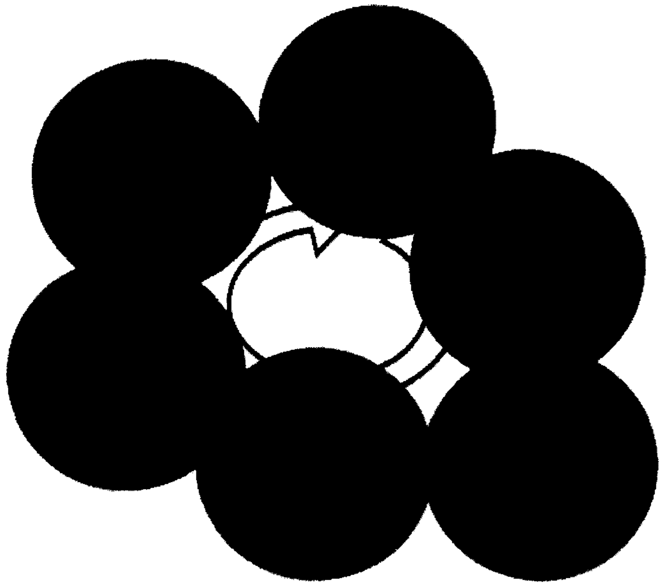


Figure 1. Six Risk Management Questions (Haimes, 2004)

These six risk management questions were developed by Haimes in 2004 and have been used in the field of risk management since then.

There are several other organizations and agencies that use the methodology of independent reviews for their P/p that have a high level of complexity and have a life-cycle cost of $500 million and more. Federal agencies such as the Department of Defense (DOD), Federal Aviation Administration (FAA), National Institutes of Health (NIH), and Department of Energy (DOE) use independent reviews to assess and evaluate their P/p.

Independent reviews for a P/p with a life-cycle cost over $250 million are required by law to report their progress to Congress and the OMB. Three elements that must be evaluated during these reviews are: (1) technical issues, (2) cost, and (3) schedule. Stakeholders require an evaluation and integration of these elements. Currently, cost/schedule analysts conduct a separate technical, cost, and schedule analysis, not an integrated method. Moreover, NASA NPR 1000.5 initiated the requirement to perform integrated cost and schedule analyses for major P/p at a specific decision point.

1.3 Research Objectives

The objective of this research is to develop uncertainty factors from NASA's actual historical project data to be used to classify risk for future cost estimations. Additionally, it supports the independent reviews which inform NASA senior management to make the right decision regarding the project's progress. This research is to provide a tool to assess project risks and provide more informative data for stakeholders and decision-makers.

1.4 Project Research Problem Areas

This dissertation focused on four core problem areas. Solution approaches were developed for each area in the form of analytic methodologies.

Problem Area 1

Determine NASA projects from which to gather data as it relates to cost growth for science missions.

Problem Area 2

Develop a method to evaluate NASA historical projects' cost by collecting coherent dataset.

Problem Area 3

Develop NASA uncertainty factors (NUFs) by capturing the trend of growth data from the selected science missions and comparing these factors with other uncertainty factors.

Problem Area 4

Bring together research and uncertainty factors developed in Problem Areas 1 through 3 into a coherent tool to be used in the quantification of risk for future NASA projects.

Figure 2 captures the project problem areas in a graphical format that includes the data collection method, data analysis, selection of missions, and testing and validation of the results.

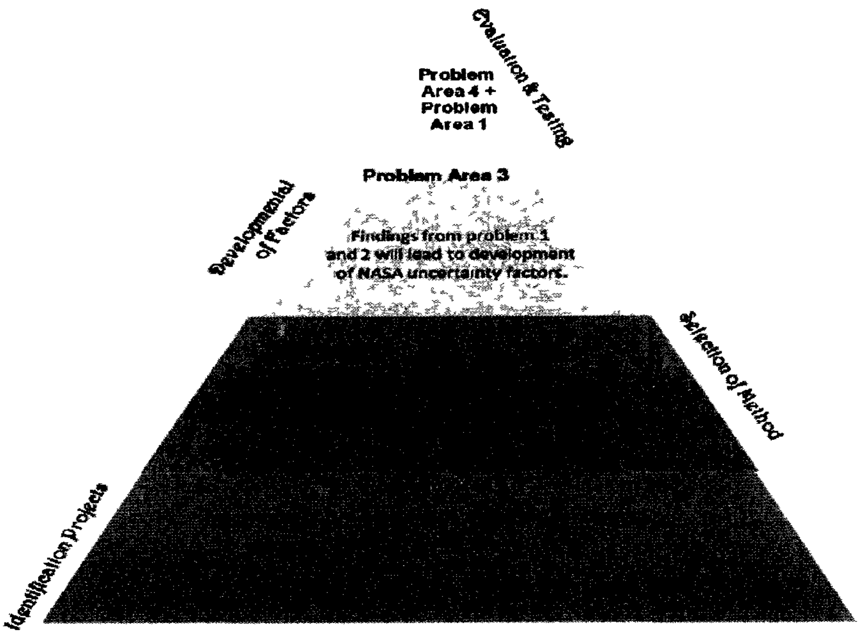


Figure 2. Research Project and Problem Area Relationship

1.5 Research Contribution

This project's contribution is to develop NASA mission uncertainty factors from actual historical NASA projects to support cost estimating and independent reviews. This provides NASA senior management with information and analysis to determine the appropriate decision regarding P/p at KDPs. These factors are tested and evaluated by statistical methods and the lognormal distribution is developed.

CHAPTER 2

BACKGROUND OF THE STUDY

2.1 Literature Review

This section separates the literature review into sub-problems in order to be able to cover related material (see Figure 3).

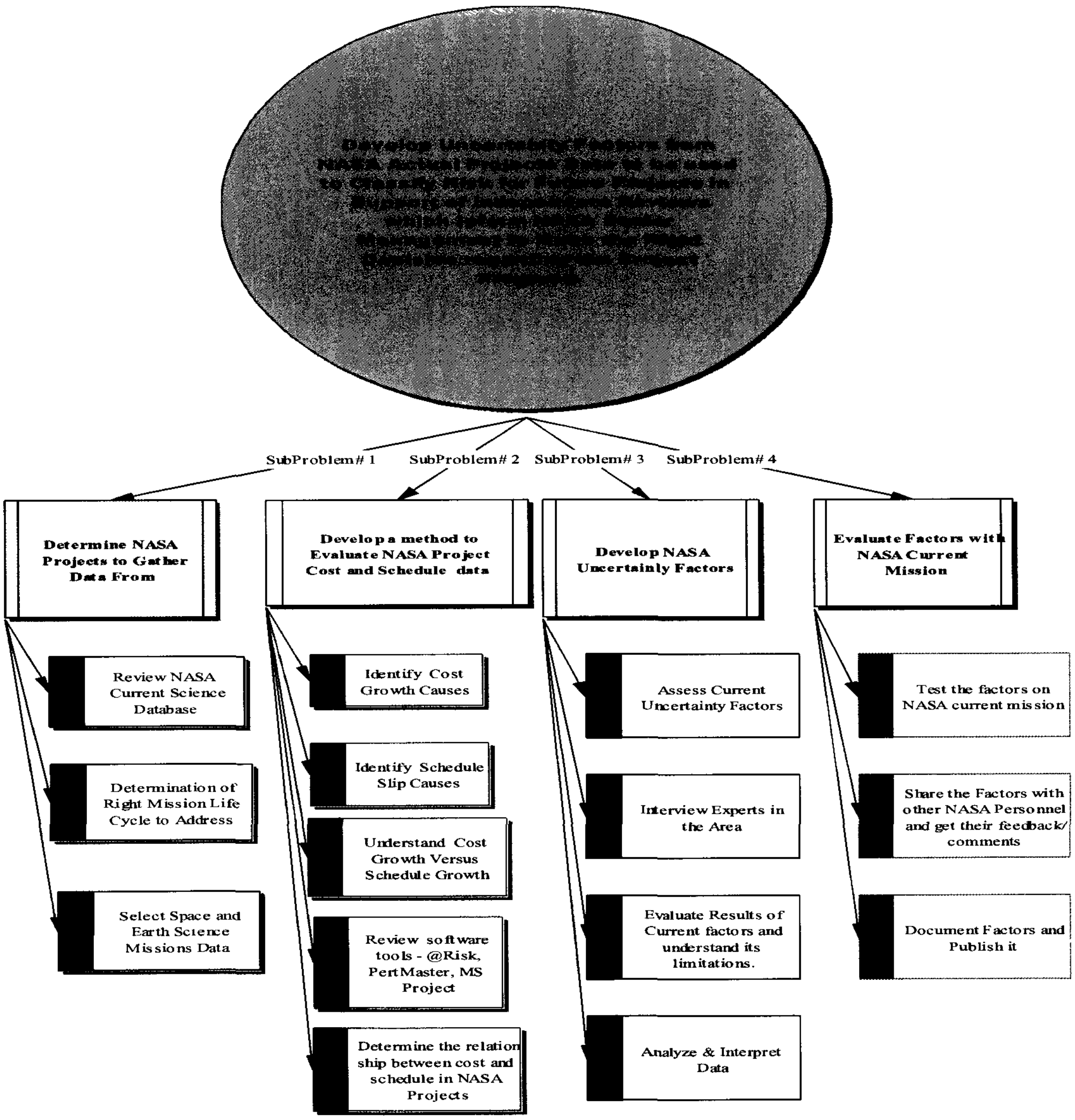


Figure 3. Research Project Problem and its Sub-Problems Literature Review

Risk management has been a major focus of NASA's culture. Risk management is defined by Ruckelshaus (1985) as the process by which the Agency decides what action to take in the face of risk estimates. Pinto (2006) has stated that risk management can be described in terms of two sets of activities: risk assessment and risk mitigation. Risk assessment can be summarized by posing the following questions (Kaplan, 1981): What can go wrong? What is the likelihood that it could go wrong? What are the consequences? After risks have been assessed, the following questions have to be posed for risk mitigation: What can be done? What are the tradeoffs? What are the impacts on future options? In this report, sustainable management of risk is accomplished by describing frameworks for: (1) valuation of avoided risks, and (2) improving outsourced information security services. NASA's risk assessment method is to avoid risk and mitigate it as described by Pinto's perspective.

Additionally, Schuyler has defined risk analysis as the discipline of helping decision-makers choose wisely under conditions of uncertainty. The quality of decision impacts cost, schedule, and performance. Most decision problems are about resource allocation: where do we put the money, time, and other resources? Decision analysis involves concepts borrowed from probability theory, statistics, psychology, finance, operations research, and management science. Also, Schuyler stated that decision analysis provides the only logical, consistent way to incorporate judgments about risks and uncertainties into an analysis. Decision analysts have to do a credible analysis that must have two main characteristics: objectivity and precision. In NASA, decisions are made in all levels of the project, but understanding risk that is associated with cost is not a clear concept at

NASA. Moreover, Arena (2006) stated that risk analysis has three areas: risk assessment, risk management, and risk communication, which interconnect and influence each other.

Cooper (2003) discussed the relationship between stakeholder expectations and project risk. NASA, as the sponsor for interplanetary exploration, provides the funding and oversight for the development and operation of all missions. However, the ultimate determination of the success or failure of any flight project is the responsibility of the stakeholders. The author developed the diagram below (Figure 4) to show the relationships of external and internal factors, communication, and inter-connectivity/ influence of each other.

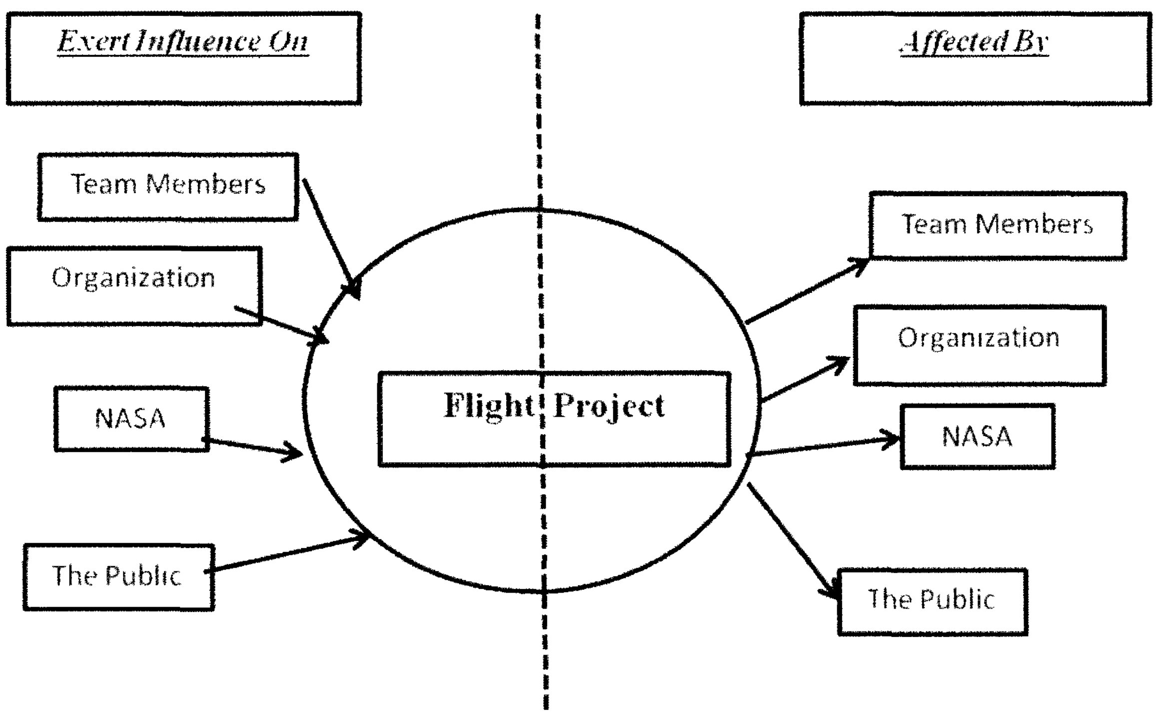


Figure 4. Success and/or Failure of a Flight Project (Cooper, 2003)

Cooper's paper addressed the extension of project risk management practices to address the management of stakeholder expectations. This concept establishes the criteria for a project's success/failure and motivates stakeholder actions. The project team will understand the stakeholders' concerns and make decisions that consider the potential impacts on the stakeholders. Through his paper is in conceptual phase, it includes a stakeholder perspective which has the potential to contribute to the overall risk management effort of a project.

More specific to NASA, Connelly (2004) wrote a paper regarding Integrated Risk Management within NASA P/p. This paper states that "the integrating risk across people, processes, and project requirements/constraints serves to enhance decisions, strengthen communication pathways, and reinforces the ability of the project team to identify and manage risks across the broad spectrum of project management responsibilities." Also, the author asserts that applying an integrated approach to risk management makes it possible to do a better job at balancing safety, cost, schedule, operational performance, and other risk elements. Integrated risk management brings project management and engineering processes together to help decision-makers make better decisions. Risk management is a deliberate activity, involves a systematic process, and covers the entire project life-cycle. Thus, integrated risk management is a process that involves the understanding of roles and responsibilities of all stakeholders on the project team.

Additionally, NASA has a Risk Management Procedural Requirement, NPR 8000.4, that is designed to identify, analyze and plan, track, and control risk to increase the likelihood of achieving P/p goals. It enables the Project Manager to manage the risks of the P/p. It is also a standardization process and a tool to assist all NASA P/p to develop a risk management plan. However, it does not look at the independent review aspect of risks and it does not address the evaluation method of risk within the project.

There is a limited amount of research and documentation regarding NASA's risk management P/p. However, this concept continues to evolve and a great deal of focus and energy are being spent to successfully integrate the risk management process across the P/p life-cycle. Various processes, tools, and techniques, management involvement, and stakeholder monitoring, all must perform and function together to achieve mission success. Every P/p undergoes an ILCR, which is the analysis of a proposed P/p by an independent team composed of management, technical, and resource experts. This team evaluates the cost, schedule, and technical performance, and provides an integrated risk assessment of the P/p to senior management. Additionally, the team conducts risk analysis, which allows decision-makers to get a better understanding of the range of possible outcomes of any decision and to identify known risk areas from experts in the field. Understanding cost and schedule risks are important components of decision-making. Decision-makers seek to understand the risks taken for association with the Agency's investment in order to make an appropriate decision.

Cost growth is a problem experienced by many types of projects in many fields of research. The measurement of cost growth has been inconsistent across programs, NASA Centers, and Congress. The Government Accountability Office and Congress generally consider the baseline to be the first time a mission appears as a budget line item in an appropriations bill, which is often before a preliminary design review. The contents of NASA estimates differ from each other and may include:

- Phases A and B, some start with Phase C,

- Launch costs and/or mission operations, and/or
- NASA oversight and internal project management costs.

These differences make it difficult to develop a clear understanding of trends in cost growth. Thus, different studies reach different conclusions, because they examine different sets of missions and calculate cost growth based on different criteria. By definition, cost growth is a *relative measure* reflecting comparison of an initial estimate of mission costs against costs actually incurred at a later time (National Research Council, 2010). This study considers only development costs.

Cost growth affects the risk of P/p. There is a great deal of literature that addresses risk and risk management in engineering research environments. Figure 3 provides a quick look at the literature review of this research.

NASA P/p conducts internal reviews to establish and manage the P/p baseline. P/p are required to document in their P/p Plans their approach to conducting P/p internal reviews and how they will support the independent life-cycle reviews. ILCRs are conducted by a SRB.

- The SRB has a single chairperson and a NASA Review Manager.
- The SRB remains intact, with the goal of having the same core membership for the duration of the P/p.
- SRB members must be independent of the P/p and some members must be independent of the Center(s) responsible for the P/p.

In the article entitled, "Building Better Boards, Harvard Business Review" by David Nadler (2004), Nadler discussed the difficulty of board building and the length of time it requires. Any board should have certain characteristics, such as the right mind set, the right role, the right work, the right people, the right agenda, the right information, and the right culture. Also, the article mentioned board building contributes not only to performance, but also to member satisfaction as an important element. This article provided a relevant perspective on cooperative boards that is very similar to independent review boards that evaluate NASA P/p.

In Dillon paper (2003), he addressed the fact that managers of complex engineering development projects face a challenge when deciding how to allocate scarce resources to minimize the risk of project failure. A new model called the Advanced Programmatic Risk Analysis and Management (APRAM), describes a decision-support framework for the management of the risk of failures of dependent engineering within projects. The model aids the decision-maker in making an informed decision on a top level risk and determines the optimal allocation of resources. Also, the model provides a proactive approach to making risk take-offs under tight resource constraints. The author concludes that NASA is challenged within the current government environment, thus it needs better risk management and independent review of technical projects.

NASA has been and continues to work the risk analysis issue. During a Cost-Risk Workshop at Langley Research Center (LaRC), Coonce (2008) stated that "the purpose of this workshop was to explain why NASA must improve its cost and schedule estimating methods, show forthcoming probabilistic estimating and budgeting policy, and explain the fundamentals of probabilistic estimating." The author stated that NASA's current projects have exceeded their launch dates by 56% and cost estimates by 64%. The cost and schedule growth are adversely affecting other projects in the portfolio as well as damaging reputation and credibility with stakeholders. In this workshop, the author stated that major NASA projects must submit budgets at a 70% confidence level (CL) starting at the initial phase of the project. Figure 5 shows the different cost estimating methods used NASA-wide. There are three methods of cost estimating parametric, analogous, and engineering (bottom up), for each phase of flight project. Estimates created using a parametric approach are based on historical data and mathematical expressions relating cost as the dependent variable to selected, independent, cost-driving variables through regression analysis. Analogy estimates are performed on the basis of comparison and extrapolation to like items or efforts. Cost data from a past program that is technically representative of the program to be estimated serves as the basis of the estimate.

The engineering method is sometimes referred to as "grass roots" or "bottom-up" estimating. The engineering build up methodology is rolls up individual estimates for each element into the overall estimate. This costing methodology involves the computation of the cost of a WBS element by estimating at the lowest level of detail (often referred to as the "work package" level), wherein the resources to accomplish the work effort are readily distinguishable and discernible. Currently at NASA, there is more emphasis on the parametric method.

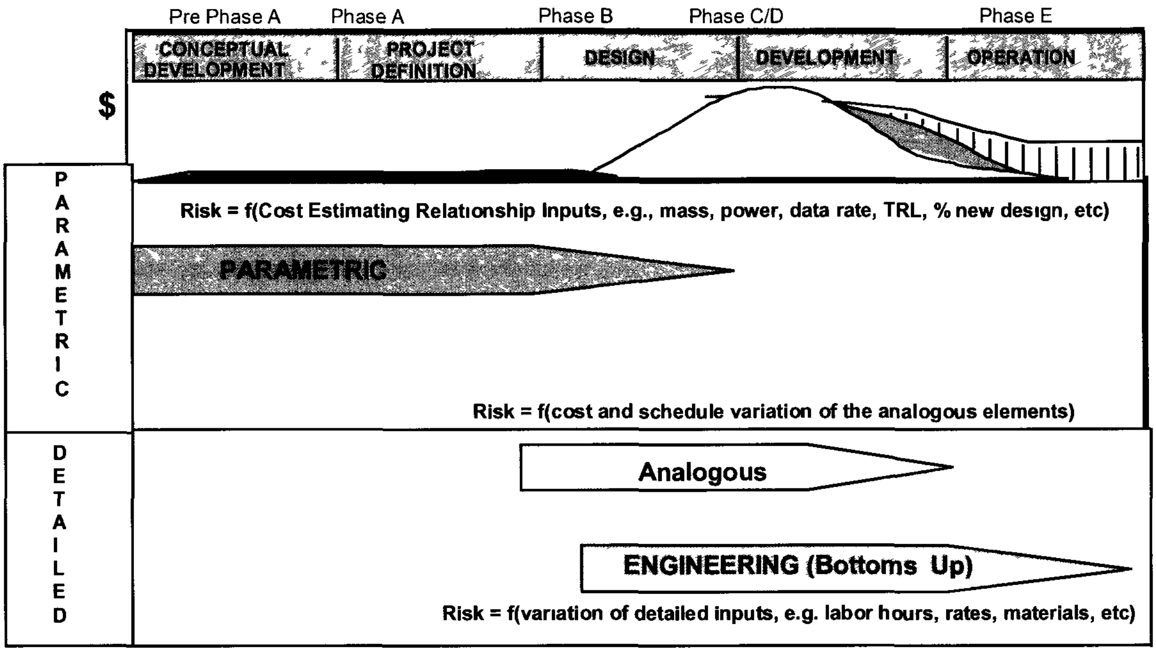


Figure 5. NASA-Wide Cost Estimating Methods (NASA Cost Estimating Handbook, 2008)

To realistically implement the 70% CL estimate policy, the P/p must: be completely transparent on how their estimate was derived and allow sufficient time for the other party to understand it; provide a basis for their respective base estimates; and provide rationale and data to explain how they derived their probability distributions. NASA Policy Directive (NPD 1000.5) has placed a new requirement on the P/p that P/p must comply with the new requirement in order to approve funding.

There are several developmental processes and methods to integrate the cost and schedule that are underway in the risk estimating field. Smart (2007) performed research on cost and schedule relationships and developed a cost model that implemented funding profiles with cost caps, cost impacts on schedule, and schedule impacts on cost. Smart stated that cost and schedule are highly correlated. For example, if the schedule slips, the cost will increase. Cost and schedule are mathematically correlated, but there is no tested and verified model that is equipped to handle cost and schedule jointly. In reality, cost and schedule estimates are analyzed and developed independently of one another. Most of NASA P/p incur schedule overruns, thus when schedule increases, costs increase due to a stretching of the funding profile. See Figure 6.

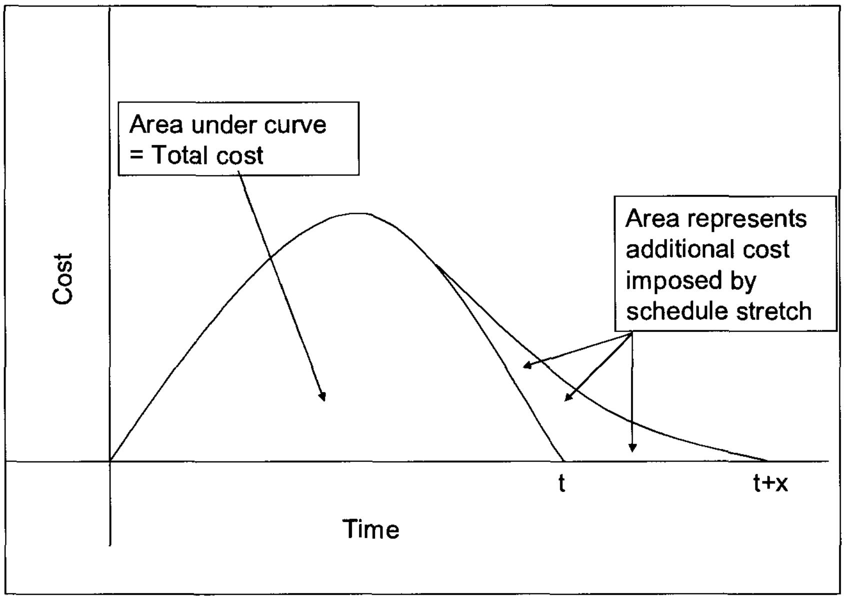


Figure 6. Cost Penalties Due to Changes in Schedule (Smart, 2007)

In conclusion, Smart stated that cost growth is sensitive to schedule growth and developed several algorithms for the effect of schedule expansion, schedule compression, and funding caps on cost. His research resulted in NASA beginning an integrated approach to cost, schedule, and risk assessment. Moreover, the Quantitative Techniques Incorporating Phasing and Schedule (QTIPS) model has been developed from Smart's research and several NASA cost and schedule analysts use this model in their analyses.

Another method was developed by David Hulett (2007). Hulett presented his paper at the 2007 NASA Project Management Challenge. He stated that schedule risk analysis is dependent on one-path schedule that has two branches: risk and probabilistic. Schedule is managed using Microsoft® Project, but cost is managed using Microsoft® Excel. Hulett developed the pictorial shown in Figure 7 to show integration of cost and schedule on project risk.

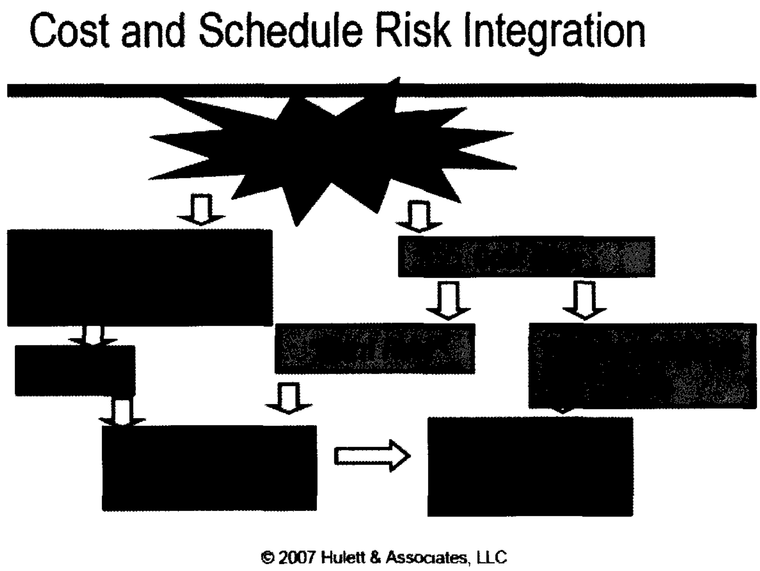


Figure 7. Cost and Schedule Risk Integration (Hulett, 2007)

Additionally, Hulett (2007) stated that schedule risk depends on the schedule logic and an uncertainty in the activity duration and also that Monte Carlo simulation is the acceptable method of estimating uncertainty from all risks. Cost risk depends on schedule uncertainty, uncertainty in burning rates, and uncertainty for time-independent costs.

Moreover, Parsons (2007) stated that problems are better prevented than solved. Data is critical for detecting and predicting potential problems; and the purpose of an independent review is to predict and plan for any risk that the project cannot detect. The independent cost and schedule analysts usually use technical and programmatic data from early missions and projects to populate their models. Thus, using a data mining package and models to predict future project risk is the core of the independent review's objective.

NASA has implemented independent reviews to assess future projects using formal project data.

Steven Grey's book entitled, "Practical Risk Assessment for Project Management," showed how to accomplish a quantitative cost and schedule risk analysis of projects and explained how to apply the same methods to forecasting revenue/profits in a project's business. These assessments are conducted independently and are not integrated. Additionally, he stated that risk models are evaluated by Monte Carlo simulation, such as the @RISK Simulation tool. He addressed the cost risk by assessing the uncertainty in the project's costs, breaking down the total cost into parts, describing the uncertainty in each part, and then putting the parts back together to give a whole picture. The standard way to break down a project is by the implementation of a work breakdown structure (WBS). The schedule risk is represented in terms of a network of linked activities with a logical structure, a more complex structure rather than a list of costs to be added. Thus, a basic form of a schedule risk model is: a network with all the dependencies between activities; a three-point estimate for the durations of all activities including contingencies and lags on links; definitions of correlation between estimates; and the probabilities associated with branching points. Finally, the author referenced several application tools, such as, @RISK for Microsoft® Project, Crystal Ball, Predict, and Monte Carlo by Primavera to be used to develop risk assessment of projects.

2.2 NASA Specifics

In the 2001 Government Accountability Office (GAO) report, the GAO stated that NASA does not have a performance measure that directly addresses the space station cost control or risk mitigation activities and contingency planning. The Program lacks a risk management plan and lacks an understanding of all aspects of the risk and its associated cost. This report has emphasized the need to understand risk and how it relates to P/p success.

Bitten et al. (2005) have shown that schedule restrictions imposed on planetary missions by fixed launch dates create higher failure rates and appear to have more cost growth due to schedule restrictions. NASA studies observed that planetary missions fail at a rate markedly higher than that of Earth-orbiting missions. They examined the relationship between schedule and risk for planetary missions; the data included 38 NASA missions. They focused on the development time and operational status and found that of the 3.9% of missions that experienced schedule growth, 30% were successful, 40% were impaired, and 30% experienced catastrophic failure rates. They recommended that development time for planetary science should be greater than 36 months and should be closer to 46 months to be consistent with the average development time for successful missions. This research provides a great approach for data analysis of historic NASA planetary science missions that could be evaluated for this current research. Additionally, it emphasizes the need to understand the cost and schedule relationship.

Kellogg and Phan (2002) developed an approach for estimating the costs of space-based instruments by using actual costs from historical instruments. They tested their approach with the NASA Goddard cost model for verification. They concluded that analogy based estimating was a powerful tool for cost estimators to use, especially in the early conceptual design phase. For this research, uncertainty factors are to be developed from NASA historical data, which is similar in methodology to that which Kellogg and Phan have recommended. Bitten, Emmons, and Freaner (2005) have addressed the question of funding profile on cost and schedule growth. The initial funding profile provided by a mission is one of many factors that can contribute to the cost and schedule growth of a mission. The results of their study indicated that certain initial funding profiles may minimize cost and schedule growth. Finally, they stated that the best choice of funding profile is made after fully understanding the development challenges of the mission, the mission development time required to successfully implementing the mission, mission requirements, and the mission acquisition approach. The authors have provided guidance as follows:

- A more balanced profile (45%-55% beta curve) may limit cost & schedule growth.
- A more back-loaded funding profile is better for missions with longer development times.
- A front-loaded profile could be managed to retain large reserves during early phases that could be carried over to later phases. This option is the best, if managed properly, and provides the most flexibility for early risk mitigation and responds to problems that occur in integration and testing (I&T).

This study provided correlation between the funding profile, cost, and schedule growth, which is an element that needs to be considered within this current project. Also, this study provides a primary source of information on NASA's fiscal year budget.

Bitten, Emmons, and Freaner have studied NASA cost and schedule growth to set reserved guidelines for future P/p. They stated that the current average cost reserve is on the order of 19% and 8% for schedule reserve for each project. From the study of 40 missions, they recommended an addition of 14% cost reserve at the program level over and above the 19% cost reserves that typically has been held at the project level. They also recommended increasing the schedule reserve to 19% in lieu of 8%. Additionally, they provided best practices for controlling cost and schedule growth in their paper and provided a comparison to industry guidelines and rule of thumb. This paper's approach is very clear and relevant to the current project of defining and categorizing the causes of cost and schedule growth for 40 missions. NASA did not embrace the result of this paper, but NASA has set a new policy since then.

The National Research Council report of 2010 entitled, "Controlling Cost Growth of NASA Earth and Space Science Missions," has focused on changes in NASA policy that would reduce or eliminate the cost growth. The report showed a very interesting trend of cost growth in the last several decades (Table 1).

Table 1. Decadal Trends in Cost Growth for NASA Missions

	Cost Growth	
	Average (%)	Median (%)
1970s	43	26
1980s	61, 81	50, 60
1990s	36	26

Source: Based on data from Schaffer, 2004

The major categories for cost growth that were cited in the report are:

- Overly optimistic and unrealistic initial cost estimates,
- Project instability and funding issues,
- Problems with development of instruments and other spacecraft technology, and
- Launch service issues.

Additionally, the report correlated data from fourteen NASA missions and developed a relationship between cost and schedule growth that is described by the following equation:

$$y = 1.23x + 0.13 \quad R^2 = 0.63$$

y is predicted schedule growth, x is the expected cost growth predicted, and R^2 is the coefficient of determination, which is the proportion of variability in a data set that is accounted for by a statistical model. This is a good initial correlation that could be used for the future project and its accuracy.

Furthermore, Bruno & et al. reported the following from a 2006 study:

- Cost history data for 21 of the 24 projects studied shows cost growth.
- Total growth from Phase B start to Estimate-to-Complete (ETC) at launch for all projects studied represents a combined impact of $2 billion to the Science Mission Directorate's (SMD) mission portfolio.
- Schedule history data indicates schedule slips for 19 of the 24 projects studied.
- 15 of the projects show a substantially increased rate of internal cost growth after Critical Design Review (CDR).
- Correlations between cost performance and development reserves, cost performance and Phase B spending, or cost performance and the percent of funds spent up to the CDR could not be found.
- Although adequate Phase B funding is a necessary condition for project success, it is not sufficient to ensure good overall cost performance.

These results are very similar to other early NASA studies and it confirmed that NASA needs to start looking at the problem from a different perspective. The report provided three significant recommendations:

(1) SMD should provide a stable external environment of fixed requirements, funding, and launch services;

(2) should require projects to improve the quality of early baseline cost and schedule estimates, to include a complete and explainable basis of the estimates (BOE) with corresponding cost and schedule detail, and include a level of reserves, determined by the projects that is commensurate with the implementation risk; and

(3) should consider minimizing or eliminating blanket reserve level requirements.

Furthermore, Butts and Linton (2009) have compiled a historical evaluation of cost and schedule estimating performance and introduced the Joint Confident Level-Probabilistic Calculator (JCL-PC). They claimed the JCL-PC corrects the overly optimistic cost and schedule estimates and effectively compensates for the unidentified risk events. They also referenced ninety-six historical projects that have an average cost growth of 93%, and a median growth of 51%. Finally, they provided nine recommendations: 1) include all risks in the JCL analysis; 2) mandate precise criteria for the JCL; 3) require all estimates to be created by a bonafide group, like the SRB; 4) recognize that cost control is important; 5) require managers to identify all elements that cause funding distress; 6) require cost estimate to be submitted in future year dollars; 7) require a more specific developmental stage of program; 8) disenfranchise the risk reward system; and 9) remove the prevailing stigma that under-runs are unacceptable.

Additionally, they have compiled 188 projects' cost and schedule growth dataset, see Appendix H.

NASA is not alone in a government that has program cost growth. The DOD's major space acquisitions increased approximately $12.2 billion, with 44% from fiscal year 2006 through fiscal year 2011. The GAO stated that the DOD needs to take more action to address unrealistic initial cost estimates of space systems (GAO-07-96). Moreover, in the Navy Shipbuilding programs, the Defense Contract Audit Agency (DCAA) criticized the shipbuilder's estimating system, specifically for material and subcontract cost.

The RAND's Report (2006) stated, in light of cost growth, DOD senior leaders in the Air Force want to generate better cost estimates that provide decision-makers with a better sense of the risk involved in the cost estimates they receive. The Air Force Cost Analysis Agency and the Air Force cost analysis community want to formulate and implement a cost uncertainty analysis policy. The report defined that cost uncertainty analysis is an important aspect of cost estimating and benefits decision-making. It helps decision-makers understand not only the potential funding exposure, but also the nature of risks for a particular program. The report emphasized the cost estimating methods; such as Monte Carlo, expert judgment, historical analysis, and sensitivity analysis. Finally, the report provided recommendations for a cost risk analysis policy for the DOD programs. This report is relevant to the current study because it provides a complete summary of cost estimating methods that are used in the DOD and could be used to mitigate NASA's similar causes of cost growth. Additionally, the cost estimating policy that the report provided could be implemented at NASA in some versions. Finally, this report confirmed that cost growth of programs is not NASA's unique problem, but that DOD has similar issues and concerns.

2.3 Current Practice

In the 2008 NASA Cost Estimating Handbook (CEH), the Cost Risk chapter states that NASA is embracing cost risk assessment to improve its reputation with external stakeholders to deliver projects on time and within budget. NASA management believes that all projects should submit budgets that are based on a quantification of all the risks that could cause the project to take longer or cost more than initially anticipated. Additionally, NASA has updated its policy to do a better job estimating project cost and Program Managers must request budget amounts that reflect a 70% probability that the project will be completed at or below this amount. NASA management recognizes it will take time to fully implement this policy and has created an interim approach for the FY 2009 guidance. Moreover, NASA has acted on the findings of the 2004 GAO Report and the *Space Systems Development Growth Analysis* report. The NASA cost estimating community is resolved to forecast cost more accurately and to account for risk. Appendix B contains the NASA Cost Risk Policy as excerpted from the CEH. The CEH reviews new measures NASA is implementing to strengthen its attention to cost risk, including:

- Distinguishing between uncertainty (lack of knowledge or decisions regarding program definition or content) and risk (the probability of a predicted event occurring and its likely effect or impact on the program).
- Identifying the level of uncertainty inherent in the estimate by conducting a cost risk assessment.
- Pushing for greater front-end definition to minimize uncertainty.

- Resisting the urge to hide or carry uncertainty forward under cost estimating assumptions.

Moreover, NASA must be able “to deliver its P/p on time and within the estimated budgeted resources,” as stated by Michael Griffin, the former NASA administrator. To accomplish this objective, the NASA Administrator, through a series of Strategic Management Council meetings, decided that all projects should be budgeted at a 70% CL based on the independent cost estimate (ICE), which can be funded by either the project, Mission Directorate, or performed by NASA's IPAO. This is one of the most important ways that NASA can improve the quality of its cost estimates and, hence, its reputation with its external stakeholders (see Appendix B). Additionally, NASA has twelve tenets of cost risk (Appendix D) that are developed based on the project risk probability distributions.

As seen from the above reviews, NASA must meet both stakeholder expectations and its own policy. Better cost estimating will enhance these expectations and allow the Program Manager, Project Manager, and the projects to better communicate the program’s cost need. Cost estimates predict future programs’ cost and there is uncertainty associated with them.

Thus, uncertainty analysis should be performed to capture the program risks. NASA has been using available uncertainty factors from Aerospace, Air Force, and Booz Allen Hamilton (BAH) to develop projects’ risk posture (Appendix F). NASA has no insight into the development of these factors, which can lead to unrealistic risks in many NASA projects.

From the literature, there is not a clear method of addressing the NUFs from historical data to assess risk of project. Thus, the development of NASA-specific uncertainty factors will provide a better cost estimate to the new P/p and move this field forward to a more realistic cost prediction.

CHAPTER 3

RESEARCH METHODOLOGY

The purpose of this chapter is to describe the basic knowledge required to collect and analyze cost data. This chapter will cover several areas of data collection methodology, data synthesizing, and data analysis. This project used programmatic methodology to address its process, which includes collecting data from different sources, evaluating by qualitatively and quantitatively logical processes and then developing NUFs, which can be generalized to future NASA projects.

3.1 Data Collection

The question of cost data availability and relevance merits requires more discussion. Most methods of assessing cost risk require some historical data, at levels of aggregation that vary widely across the different methods. To set the context regarding the magnitude of cost growth and using cost growth as a proxy for cost risk, the NASA historical experience of cost growth on fifty missions will be explored. This study of cost growth is difficult because of a method for recording project cost, technical issues, and schedule data must be developed and implemented. These data are not recorded in a standardized format and collected at a reasonable frequency. The depth at which the data are collected is not dependent on the maturity of the project. The data is not consistent across the life of the project so that, at project end, analysts can evaluate the data across the years without ambiguity.

The goal of this project is to use historical NASA cost growth to develop NUF in estimating risk during projects' initial phases of development. NASA has a vast of sources that house cost information. Over the years, NASA has developed a database to document the cost of its missions. Using these data, with other supplementary information, this project examined cost growth history to understand the cost growth data distribution and to develop specific NASA uncertainty factors. This project has acquired the data from three different sources:

a. NASA Fiscal Year Budget Estimates:

One source of information for the basis for cost growth is the NASA Fiscal Year Budget Estimates. These documents are publicly released in February of each year and display the cost and major milestones of NASA's major programs. Other researchers have acquired and collected data on NASA Earth and Space missions to address different goals. Bitten et al., Smart, and Butts' papers have all investigated recent NASA cost and schedule growth history for science missions. These missions included both Space and Earth Science missions, Aeronautics, Space Operational missions, and other Programs. An examination of this historical data has shown that such space projects often experience higher costs relative to initial estimates and project plans. For this study, Freaner's data was investigated and categorized to develop the NASA uncertainty factors. Thus, this project used data for forty NASA missions as the basis for the cost growth that was collected by Freaner's team. These missions are shown in Table 2.

b. Cost Analysis Data Requirement (CADRe):

It has been difficult to obtain technical and cost information on NASA space flight systems. Once a mission was launched, personnel were reassigned and development data was lost or thrown away. In December of 2003, NASA initiated a document action process that would capture technical and cost information regarding NASA missions at various points during the life of the mission. This document was called the CADRe and was incorporated into the NPR 7120.5 series *NASA Space Flight Program and Project Management Requirements*. The CADRe data constitutes one of the better ways to track cost estimates and schedules for major NASA missions. Over the past several years, NASA has collected and organized cost data from project managers, the budget office, and mission directorates as a basis for complete project data. Much of the data for this project was obtained from the CADRe that NASA has prepared on each of the missions studied. For this project, ten other completed missions have been added to the data. Thus, this project will investigate fifty completed missions and ten still active projects' missions (see Table 2).

c. GAO Reports:

Several science active missions are included in this study, which were obtained from GAO reports and cost analysts from NASA. The GAO report of 2011 has stated that there are 21 NASA projects with a combined life-cycle cost that exceeds $68 billion. This report has been used to verify some of the active missions' data used in this investigation. Table 2 provides the data used in this project, which are of two types: completed missions and active missions. The active missions are considered an estimate of cost growth.

Figure 8 summarizes the collection procedure from the three sources and demonstrates that data was verified several times to ensure accuracy of the result, which created a NASA data set to be evaluated for this project.

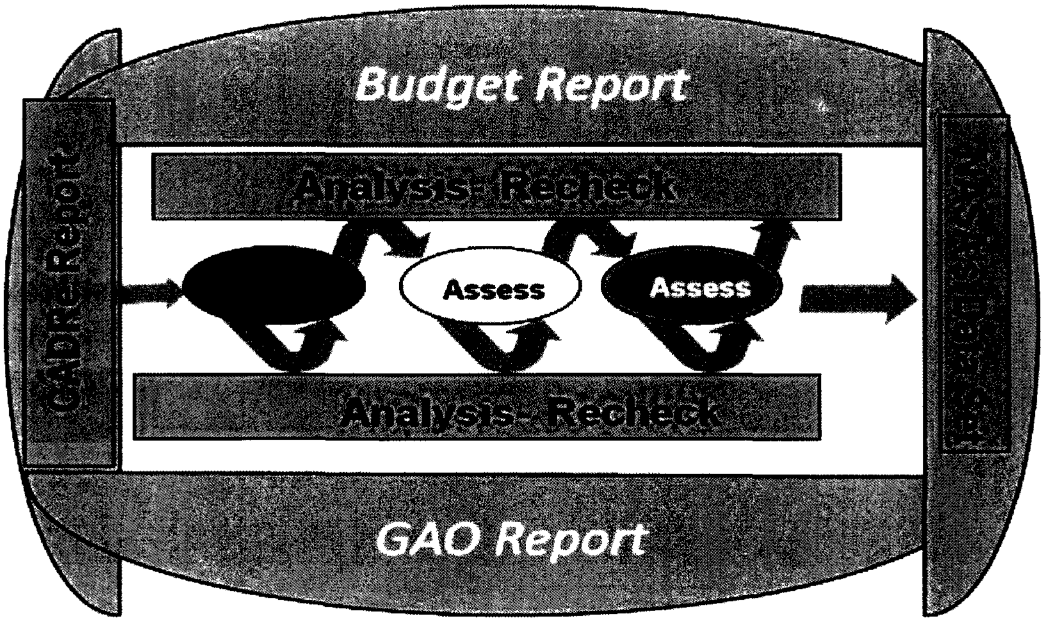


Figure 8. Project Data Collection Procedure

3.2 Data Management

The data for this research project has been managed as described in the flowchart found in Figure 9. Sixty missions were collected for this project; and thirty nine were used to develop the NASA uncertainty factors. Five completed missions were used to test the results.

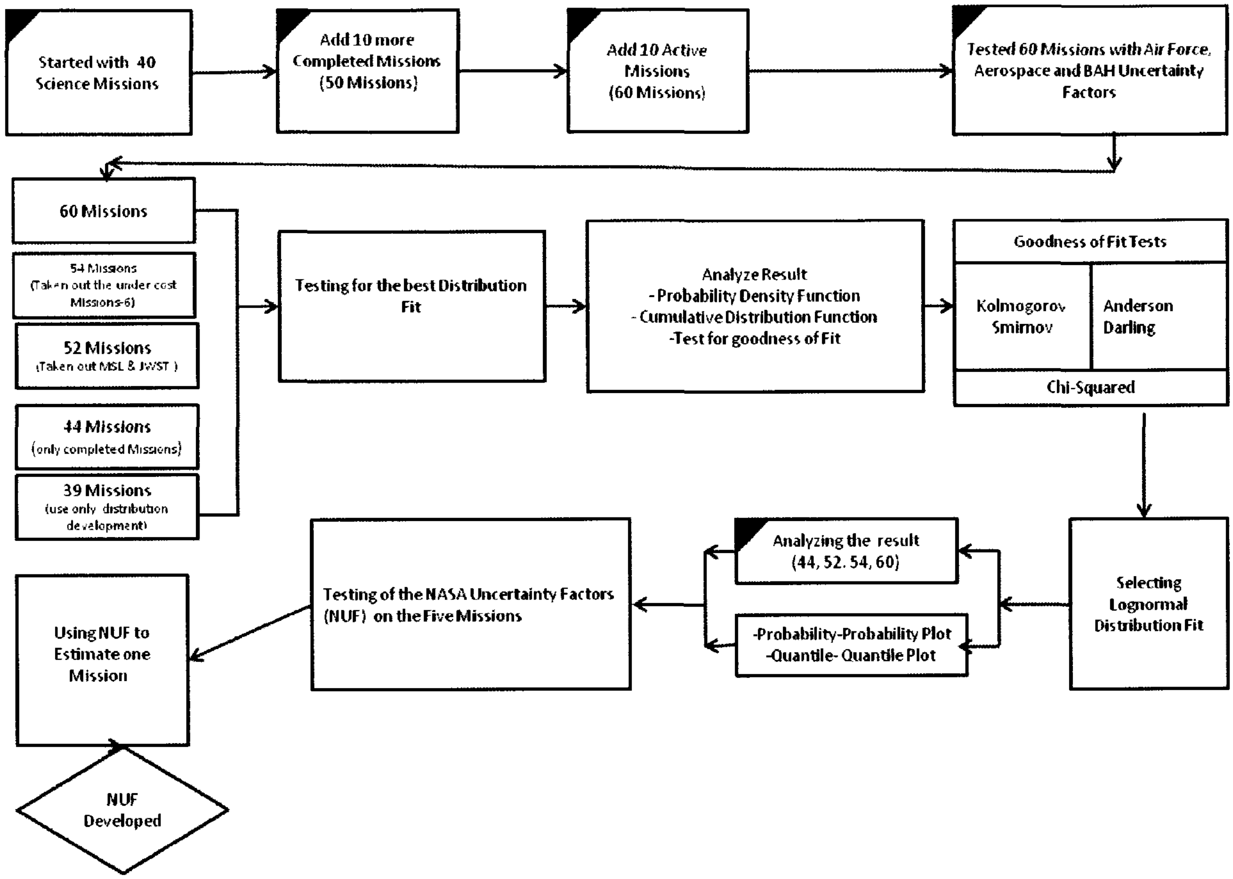


Figure 9. Project Flowchart of Data Collected, Used, Tested, and Assess

3.3 Project Data Analysis

Table 2 has the summary of the investigated missions for this project.

Table 2. Summary of Missions Investigated

Completed Missions					Active Missions
NEAR	MER	HESSI	EOS-Aqua	AIM	JUNO
LUNAR PROSPECTOR	MRO	GALEX	EOS-Aura	DAWN	AQUARIUS
GENESIS	FAST	SWIFT	LANDSAT-7	PHOENIX	LDCM
MESSENGER	SWAS	GRACE	TRMM	GLAST	NPP
MARS PATHFINDER	TRACE	CLOUDSAT	TIMED	KEPLER	GPM
STARDUST	WIRE	CALIPSO	GRAVITY PROBE B	SDO	MMS
CONTOUR	ACE	DS-1	THEMIS	WISE	JWST
DEEP	FUSE	EO-1	HETE-II	NEW HORIZONS	MSL
IMPACT MGS	IMAGE	SIRTF	SORCE	LRO	RBSP
MCO/MPL	MAP	STEREO	ICESAT	OCO	GRAIL

For this investigation, the development cost is defined as the Phases B-D and does not include the launch vehicle cost or operational cost. Figure 10 shows the NASA phases of the development from the start of Phase B to the end of Phase D.

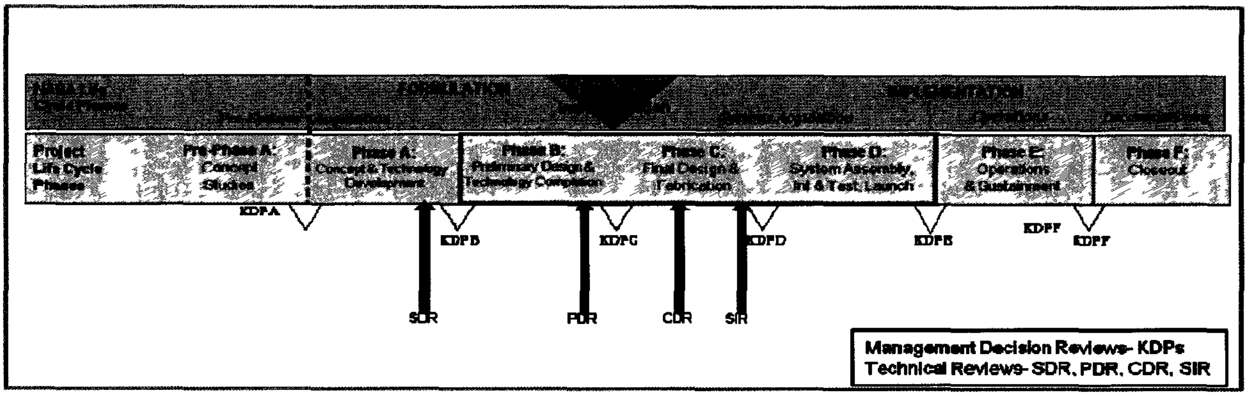


Figure 10. NASA's Life-Cycle Reviews for Flight Projects (NASA NPR 7120.5)

Figure 11 displays two important factors: initial/final cost and the percentage of cost growth. The percentage of cost growth of the mission dataset is shown in Figure 11 by the line chart on the secondary y-axis. For comparison purposes, the development initial cost is compared with actual cost from the start of Phase B to the end of Phase D. In this chart, the mean of the fifty completed missions' development cost growth is approximately 30%.

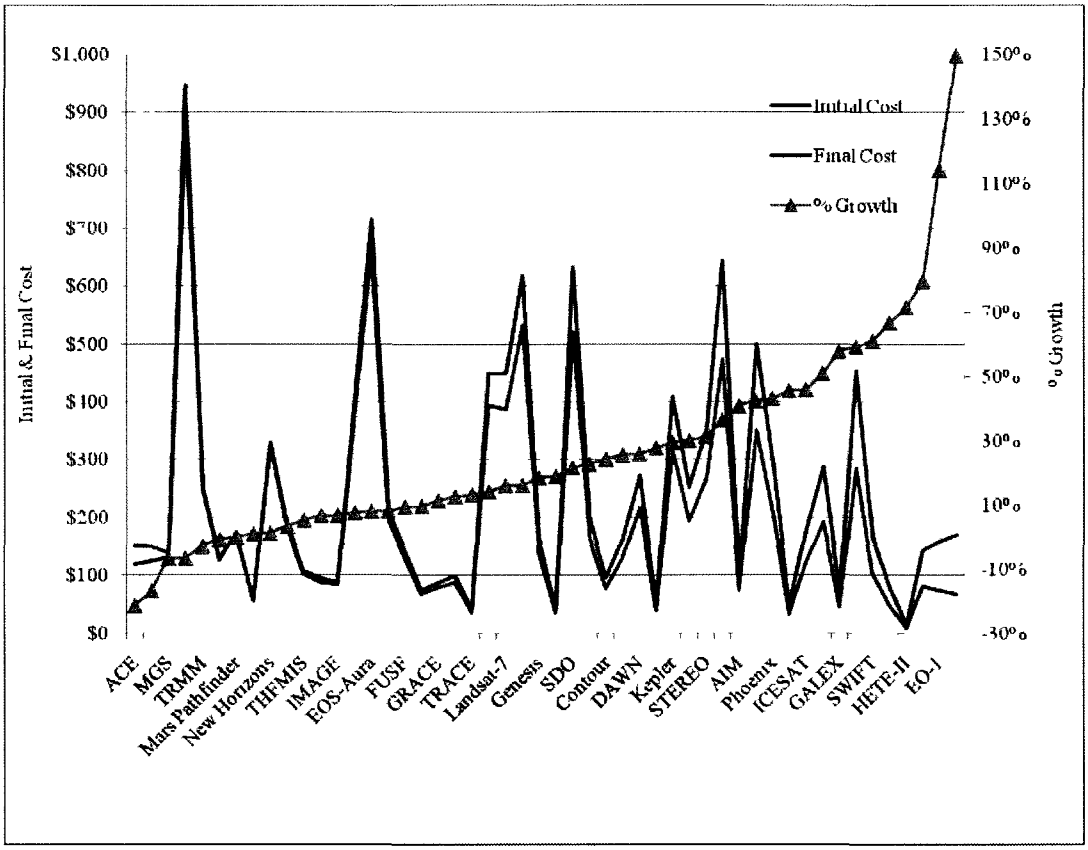


Figure 11. Initial and Final Cost for 50 Completed Projects including Cost Growth Percentage

Additionally, ten activity missions have been studied in this investigation and have seen cost growth in the cost estimating already from PDR to CDR, or SIR, as shown in Figure 10. There are two other missions, Mars Science Laboratory and James Webb Space Telescope, which were considered for the study, but their cost growth is 114% and 240%, respectively. These two missions are very complex and have a greater funding profile than most NASA science missions. Several runs were conducted including these two missions; however, the purpose of Figure 12 is to share the other missions' cost growths and ensure they are noticeable.

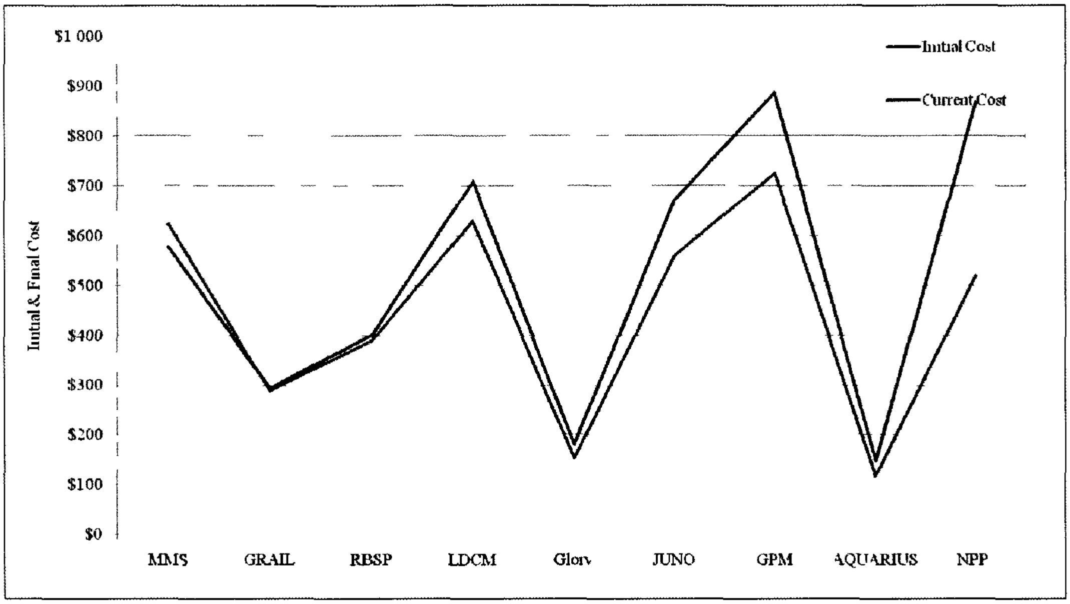


Figure 12. Initial and Current Cost for 9 Active Projects

3.4 NASA Data Analysis

To be able to understand the collected data, one must analyze the data in different ways to get more insight and understanding. One method is to use the historical cost growth as a proxy for the cost uncertainty. This method provides not only the average cost growth for past estimates, but also variability in that growth risk. Figure 13 displays the percentage of cost growth and the number of completed missions in the histogram chart. This chart shows that the data distribution is a bi-modal pattern. Most of the mission has expected cost growth of 10-30%, and more risky missions can have cost growth of more than 100%, such as MSL and JWST.

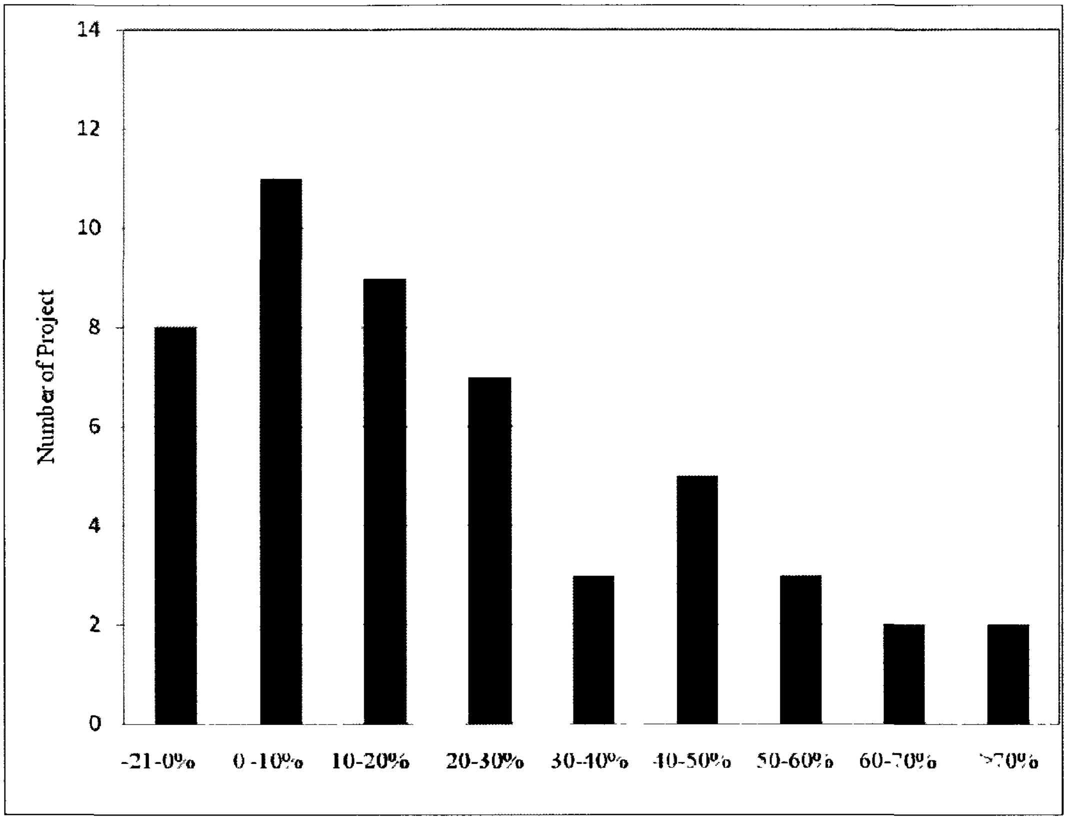


Figure 13. Percentage of Cost Growth 50 Completed Missions

When adding the ten active missions, the pattern did not change and the bi-modal trend was noted. Figure 14 shows sixty investigated missions that have cost growth and have a very similar pattern to the fifty missions. Actually, the greater than 100% active missions have increased by 3 times as the completed missions. This indicates that the active missions have a higher cost growth than completed missions.

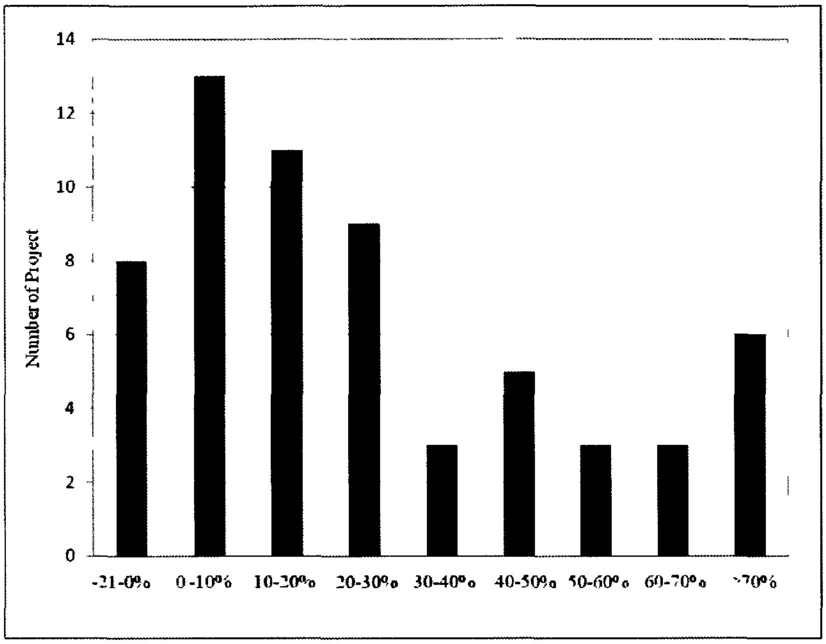


Figure 14. Percentage of Cost Growth for 60 Missions

In 2003, McCrillis developed Figure 15 from the DOD's 142 systems data entitled, "Cost Growth of Major Defense Programs." This distribution is very similar to the NASA sixty missions shown in Figure 14. The similarity contributed to the high risk and uniqueness of these two agencies. Additionally, it shows that smaller-sized projects tend to have much greater uncertainty in the initial estimates and are the source of the largest magnitude cost growth. Moreover, larger-sized projects tend to experience more reasonable cost growth, although 100% cost growth is not unexpected.

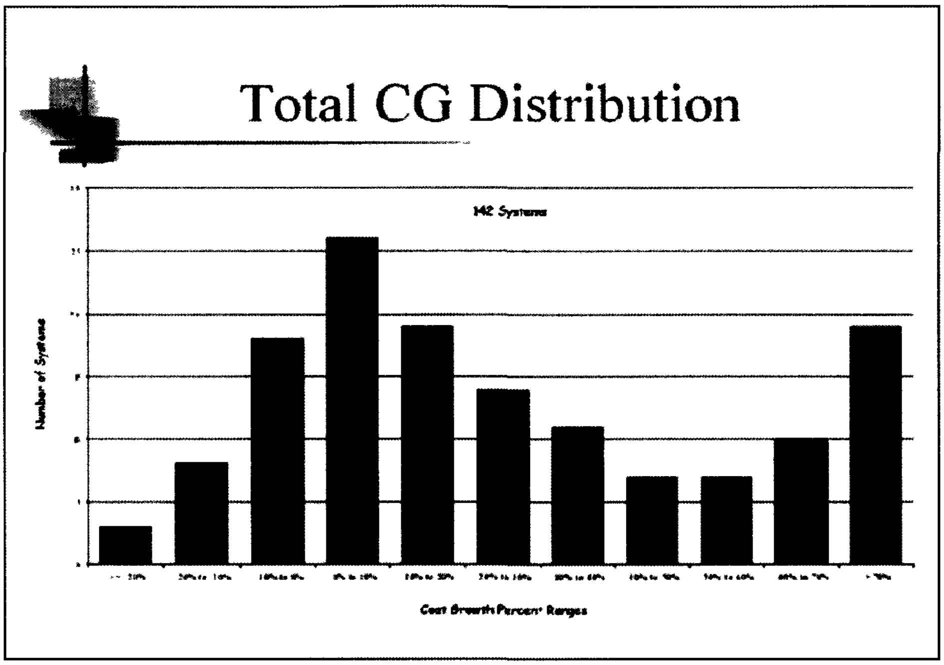


Figure 15. DOD Cost Growth Distributions for 142 Systems (McCrillis, 2003)

Bearden (2000) stated that each bar's height represents the percentage difference between a satellite's estimated cost and its actual cost in Figure 16. It has the same profile as shown in Figure 14 and Figure 15, which is the bi-modal distribution of the cost growth from multiple sources. Bearden explained that a cost-percentage comparison that makes use of an older model and the updated dollars-per-kilogram relationships are used to estimate modern small-satellite costs.

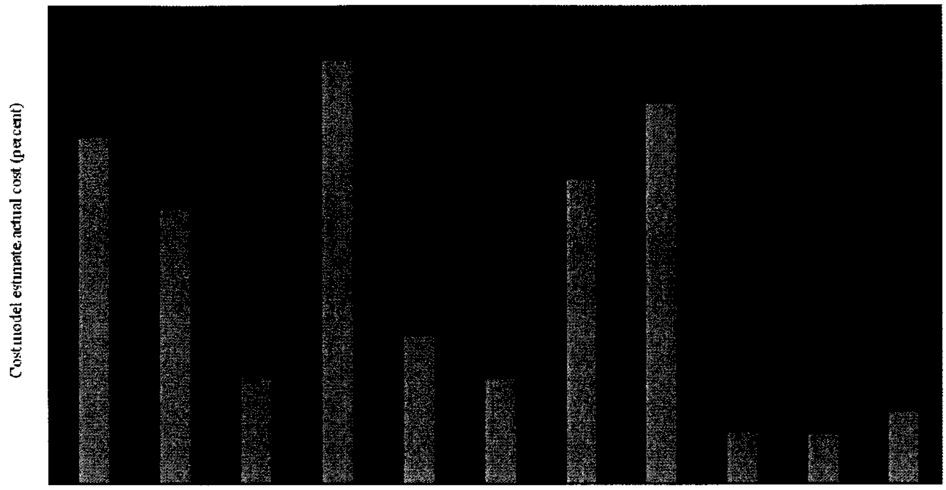


Figure 16. Small Satellite Cost Study (Bearden, 2000)

Moreover, NASA historical data showed that most of the mission's cost growth lies between 10-30% of its initial cost planned. Figure 17 shows the range from -20% up to 450% cost growth, which is based on what information was included in the data set. For this project, further analysis of the cost growth data indicated that the average total cost growth for completed missions was 30% during only the development phase of the project.

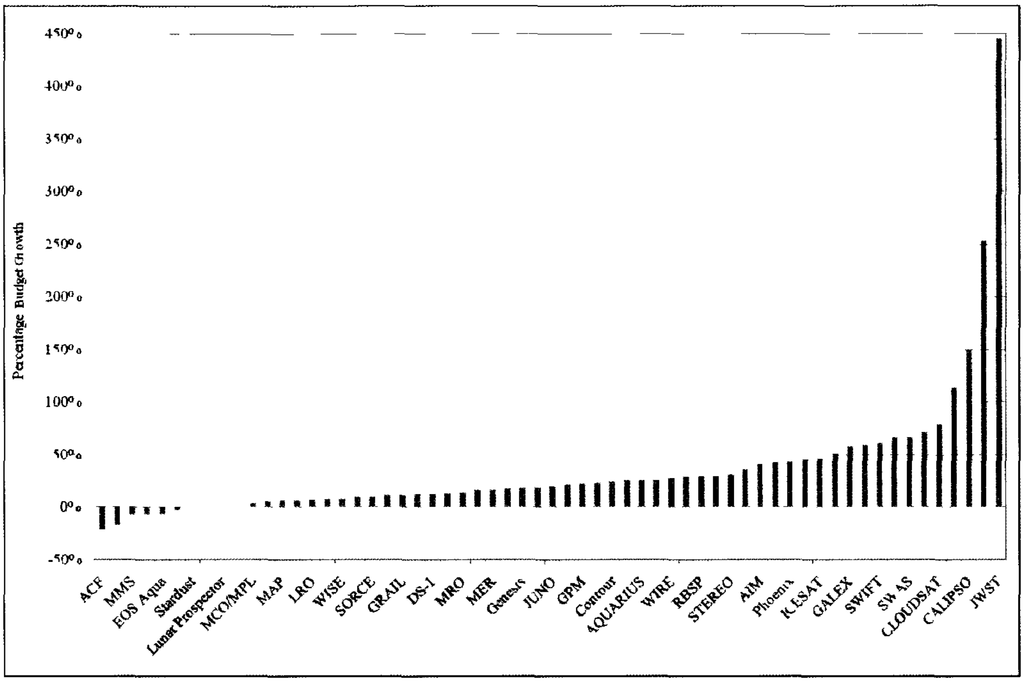


Figure 17. NASA 60 Historical Missions Cost Growth

There are a significant number of missions that experienced cost growth. What are the main causes of the growth? One can understand that space businesses are complicated, challenging, and one-of-kind. The space industry has been building space-based instruments and spacecraft for over 40 years. Experience, lessons learned, and realistic planning should reduce the cost growth. Most of the cost growth is classified as related to instrument technical development challenges, spacecraft technical problems, due to test failures, due to overly optimistic heritage assumptions, and due to management problems. A snapshot of the causes of these missions' cost growth is summarized in Table 3. The most commonly identified factors, which have been cited by other formal studies are the following:

- Overly optimistic and unrealistic initial cost estimates,
- Project instability and funding issues,

- Technology level readiness,
- Assessment of heritage,
- Problems with development of instruments and other spacecraft technology, and
- Launch service issues.

Table 3. Cost Growth Reasons for NASA Selected Missions

Mission	% Cost Growth	Reason for Cost Growth
ACE	-21.4%	No major programmatic or technical delays
NEAR	-16.8%	No major programmatic or technical delays
MGS	-6.8%	No major programmatic or technical delays
EOS-Aqua	-6.6%	Launch delay & delayed observatory I&T
TRMM	-2.8%	Launch delay due to Japanese H-II launch vehicle problems
Stardust	-0.8%	No major programmatic or technical delays
Mars Pathfinder	0.0%	No major programmatic or technical delays
Lunar Prospector	1.0%	Launch delay due to Athena launch vehicle and conflict with Cassini launch
New Horizons	1.2%	Design stability issue
MCO/MPL	3.3%	Severe programmatic cost and schedule pressure lead to failure of both spacecraft
THEMIS	5.2%	Problems with main contractor lead to cost growth
MAP	6.7%	Technical problems due to electronic parts and problems with thermal blanketing
IMAGE	6.7%	Launch delay
LRO	7.6%	Heritage complexity, thermal environment and launch delay
EOS-Aura	8.1%	Instrument deliveries delayed due to technical problems
WISE	8.2%	Design stability, Structural model failure during vibration testing
FUSE	9.4%	Problems with Fine Guidance Sensor lead to delay
SORCE	9.6%	Delays in bus and instrument deliveries
GRACE	11.5%	Problems with instrument development led to delays
DS-1	12.6%	Technical problems with introducing new technologies
TRACE	13.2%	Difficulties with instrument development
MRO	14.1%	Problems uncovered during environmental testing
Landsat-7	16.0%	Instrument deliveries delayed due to technical problems

Mission	% Cost Growth	Reason for Cost Growth
MER	16.1%	Resolving mass & schedule problems
Genesis	18.5%	Spacecraft subsystem late delivery then launch delay
FAST	18.9%	Launch vehicle delay caused by Pegasus failure
SDO	21.6%	Complexity of heritage technology, contractor performance, and funding issues
OCO	22.7%	Design stability and contractor performance
Contour	24.3%	Technical and staffing problems at APL
TIMED	25.6%	Launch slip due to technical problems encountered by the Jason 1 spacecraft
DAWN	25.8%	Technical problems, launch date, contractor performance, heritage complexity
WIRE	27.7%	Difficulties with instrument development
Kepler	29.5%	Substantial problems with instrument development & contractor performance
Deep Impact	30.0%	Technical and management problems at Ball
STEREO	31.3%	Problems with instrument growth & staffing
SIRTF	36.3%	Substantial problems with instrument development and software on spacecraft
AIM	40.8%	Difficulties with instrument development
Gravity Probe B	42.4%	Cost growth due to various unanticipated technical challenges, late delivery of payload.
Phoenix	43.2%	Technical Problems
HESSI	45.6%	Test equipment failure and launch delay due to Pegasus
ICESAT	45.9%	Significant delays in GLAS instrument development
Messenger	51.0%	Late delivery of instruments and integration problems
GALEX	57.9%	Severe problems with telescope and spacecraft
GLAST	59.3%	Design stability and complexity of heritage technology
SWIFT	61.0%	Problems developing BAT instrument
SWAS	66.8%	Launch vehicle delay caused by Pegasus failure - Spacecraft went into storage
HETE-II	71.4%	Problems requiring additional testing and delays with Pegasus Launch Vehicle
CLOUDSAT	79.6%	Problems with High Voltage Power Supply combined with Launch Vehicle Delay
EO-1	114.2%	Technical Problem, adding Hyperion instrument and launch delay

Mission	% Cost Growth	Reason for Cost Growth
CALIPSO	149.7%	Problems with LIDAR instruments combined with Launch Vehicle Delay
MMS	3.3%	Technology maturity and partner performance
GRAIL	1.2%	Heritage complexity and launch manifest
LDCM	15.4%	Technology maturity and partner performance
GLORY	17.8%	Technology maturity, contractor performance and design stability
JUNO	20.0%	Design stability and development partner performance
GPM	22.3%	Technology maturity, and funding issues
AQUARIUS	25.7%	Design stability and partner performance
NPP	50.0%	Technology maturity and design stability
MSL	114.3%	Technology maturity and design stability
JWST	242.3%	Complexity of heritage technology and funding issues
Average	*30.8%*	*Most of the last Ten missions are in CDR or SIR*

3.5 Non-NASA Uncertainty Factors

NASA has historically underestimated and underfunded the cost of new missions. In the NASA environment, cost data is limited and accurate cost estimating is a significant challenge, as stated previously. Given this environment of limited data and substantial uncertainty associated with predicting the future, for best decision support, it is imperative that analysts quantify the confidence or uncertainty of their estimates. Cost analysts try to develop the best cost estimates possible from the available information. The most common approach is to develop a "most likely", "optimistic", and "pessimistic" estimate for each component in the mission. Because every assumption that drives a cost estimate represents a point within a range of possible values, an estimate of this type is called the "point estimate," which carries specific risk within. No matter how much effort is applied to the lower elements in the estimate, total levels in the point estimate do not reflect a "most likely" value in most cases.

Uncertainty occurs for a number of reasons. The objective of the cost uncertainty analysis is to estimate the uncertainty of the point estimate and provide a basis for assessing its uncertainty or variability for a specific estimate. Because the point estimate is based on assumptions with associated uncertainty, the analyst must consider risk and uncertainty from the very outset of the project or estimate. Uncertainty is sometimes expressed as a probability distribution of outcomes; the greater the width of the distribution, the more uncertain the outcome. Uncertainty factors play an important role in cost estimation because the amount of uncertainty around an estimate is information that helps the decision-maker.

Additionally, risk analysis is an important component of a decision-making process. It allows decision-makers to get a better understanding of the range of possible outcomes of any decision—in other words, how good or bad the outcome might be and how uncertain the outcome is. Risk analysis also helps the decision-making process by identifying known risk areas. In some cases, such information can be used to mitigate areas that are high risk. Risk analysis brings more information which, in turn, generates more realistic expectations.

Uncertainty in cost estimating creates concern. Uncertainty of an estimate is tied to a risk: the more uncertain the estimate, the greater the chance of an adverse or unexpected outcome. Uncertainty of an estimate can reflect both financial risk and operational risk to the Agency, which can damage its image and reputation. Thus, to characterize cost uncertainty is to characterize cost risk. Understanding cost risk is an important component of decision-making. Decision-makers seek to understand the risks they assume with any type of investment or program. Greater cost risk might require increased management oversight to reduce or mitigate the risks identified, or to provide more reserve funds.

NASA cost analysts are using three different types of uncertainty factors that were developed by:

1. The United States Air Force,
2. The Aerospace Corporation, and
3. Booz Allen Hamilton (BAH).

NASA has no insight into the methodology and the data that developed these factors; and they do not represent NASA missions. Table 4, Table 5, and Table 6 display the Air Force, Aerospace Corporation, and BAH uncertainty factors, respectively. The Aerospace UFs are obtained from the 2010 Aerospace Study of twenty SMD projects. BAH UFs are obtained from a study that BAH performed; this information was proprietary. These factors have been used for several NASA missions, such as MMS and LDCM. Finally, the Air Force has been used in several NASA missions such as Global Precipitation Measurement (GPM) and Radiation Belt Storm Probe (RBSP).

Table 4. Air Force Uncertainty Factors

Level	Optimistic	Most Likely	Pessimistic
Low	0.95	1	1.1
Low Plus	0.96	1	1.23
Moderate	0.97	1	1.36
Moderate Plus	0.98	1	1.49
High	0.98	1	1.61
High Plus	0.99	1	1.74
Very High	1	1	1.87
Very High Plus	1	1	2

Table 5. Aerospace Corporation Uncertainty Factors

Level	Low 10%	Mid 50%	High 90%	SEE
Low	0.977	1	1.117	0.05
Medium Low	0.932	1	1.35	0.15
Medium	0.887	1	1.583	0.25
Medium High	0.842	1	1.816	0.35
High	0.797	1	2.05	0.45
high +	0.752	1	2.5	
Very High	0.707	1	3	
Very high +	0.662	1	4.5	
Extra high	0.617	1	6	

Table 6. Booz Allen Hamilton (BAH) Uncertainty Factors

	Current Baseline Schedule		
Complexity	Aggressive	Most Likely	Conservative
Very Low	N(1.20, .05)	N(1.00, .05)	N(0.8, .05)
Low	N(1.20, .15)	N(1.00, .15)	N(0.8, .15)
Moderate	N(1.20, .25)	N(1.00, .25)	N(0.8, .25)
High	N(1.20, .35)	N(1.00, .35)	N(0.8, .35)
Very High	N(1.20, .45)	N(1.00, .45)	N(0.8, .45)

	Conservative		Aggressive
Level	Optimistic	Most Likely	Pessimistic
Very low	0.850	1	1.300
Low	0.950	1	1.500
Moderate	1.050	1	1.700
High	1.150	1	1.900
Very High	1.250	1	2.100

Assumptions
-Used conservative of 0 8 and added 1 sigma
-Used pessimistic of 1 2 and added 2 Sigma

As noted above, this lack of information about the methods used to develop these factors introduced skepticism. These factors have been tested in the NASA historical completed missions in the middle range only, as shown in the yellow highlighted rows. The approach is known as the *3-point range.* This approach is currently being used by NASA to report project cost estimates. In fact, factors are called an estimate in terms of high, mid, and low points and may in fact be easier for the experts to provide rather than identifying a specific value. Figure 18a displays an example of cost risk using the 3-point range method. Each point −optimistic, most likely, and pessimistic−represents an estimate with a different set of assumptions (see Figure 18b). These assumptions can directly reflect the project's specific technical and programmatic risks. These points are the possibility of showing a 3-point range determined by a probabilistic assessment.

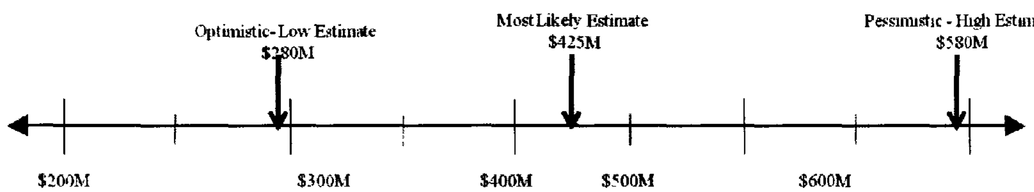


Figure 18a. A Prototype of 3-Point Range Estimate

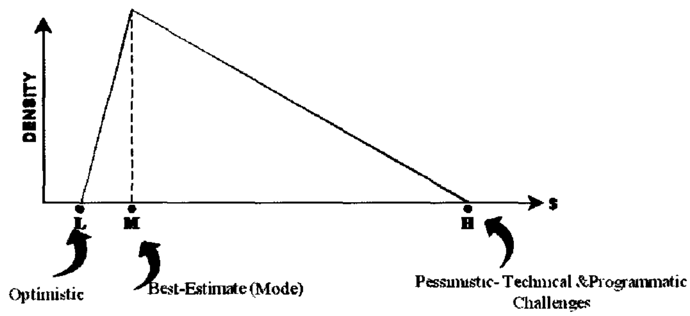


Figure 18b. Another Diagram to Demonstrate 3-Point Range Estimate

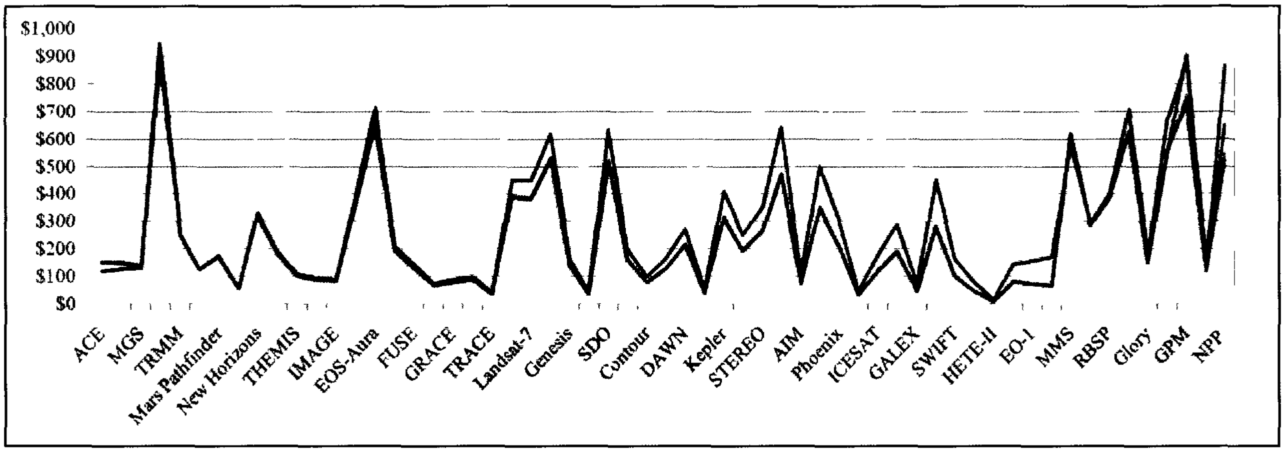
For the purposes of this project, three risk levels have been selected to test: moderate, high, and high plus. Additionally, the data was tested and analyzed for optimistic and pessimistic cases only. These cases are shown in Table 7.

Table 7. Selected Uncertainty Factors for Three Risk Levels

Level of Risk	*BAH Uncertainty Factors Selected*		
	Optimistic	**Most Likely**	**Pessimistic**
Moderate	**1.050**	**1**	**1.700**
High	**1.150**	**1**	**1.900**
Very High	**1.250**	**1**	**2.100**
Air Force Uncertainty Factors Selected			
Moderate Plus	**0.98**	**1**	**1.49**
High	**0.98**	**1**	**1.61**

High Plus	**0.99**	**1**	**1.74**
Aerospace Uncertainty Factors Selected			
Medium High	**0.842**	**1**	**1.816**
High	**0.797**	**1**	**2.05**
high+	**0.752**	**1**	**2.5**

The NASA data collected for cost risk analysis will be used to empirically validate three uncertainty factors and their associated level of risk analyses. Such a validation would help to improve both the understanding of the given uncertainty values and quality of these factors in the estimation of NASA cost risk process. It is vital to the credibility of both cost estimates and cost risk analyses to demonstrate how well they have predicted NASA mission cost. Figure 19 displays the NASA historical data using the Air Force uncertainty factors for optimistic and pessimistic. Using the Air Force optimistic uncertainty factors does not provide the correct prediction of NASA missions as seen in the figure. Keep in mind that the initial cost is often budget-driven. For example, for the AO missions, the initial "cost" is really the "budget" that the project has been given. For the optimistic case, these factors missed the actual final NASA cost of almost 90% of the missions, but for the pessimistic case, they overestimated all NASA missions.



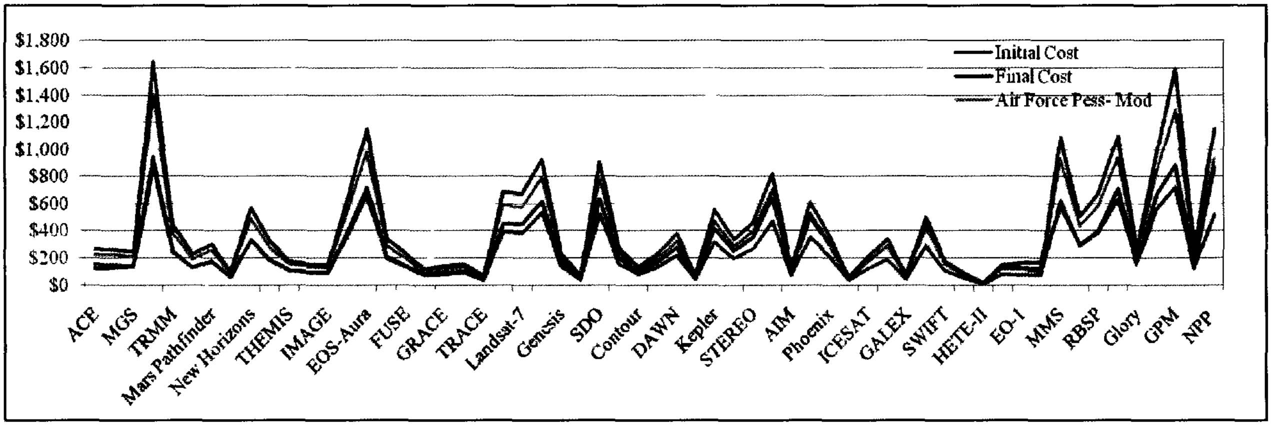


Figure 19. Air Force Optimistic & Pessimistic Uncertainty Factors & NASA Historical Missions Data

Figure 20 displays the NASA history data and applies the Aerospace uncertainty factors for optimistic and pessimistic. As seen from the figure, these factors do not come close to the actual NASA data. Thus, they are not valid factors to use to predict cost estimation of NASA missions. As seen in Figure 20, the optimistic case, it was underestimating NASA data and, for the pessimistic case, these factors predicted a much higher estimate than the actual NASA cost.

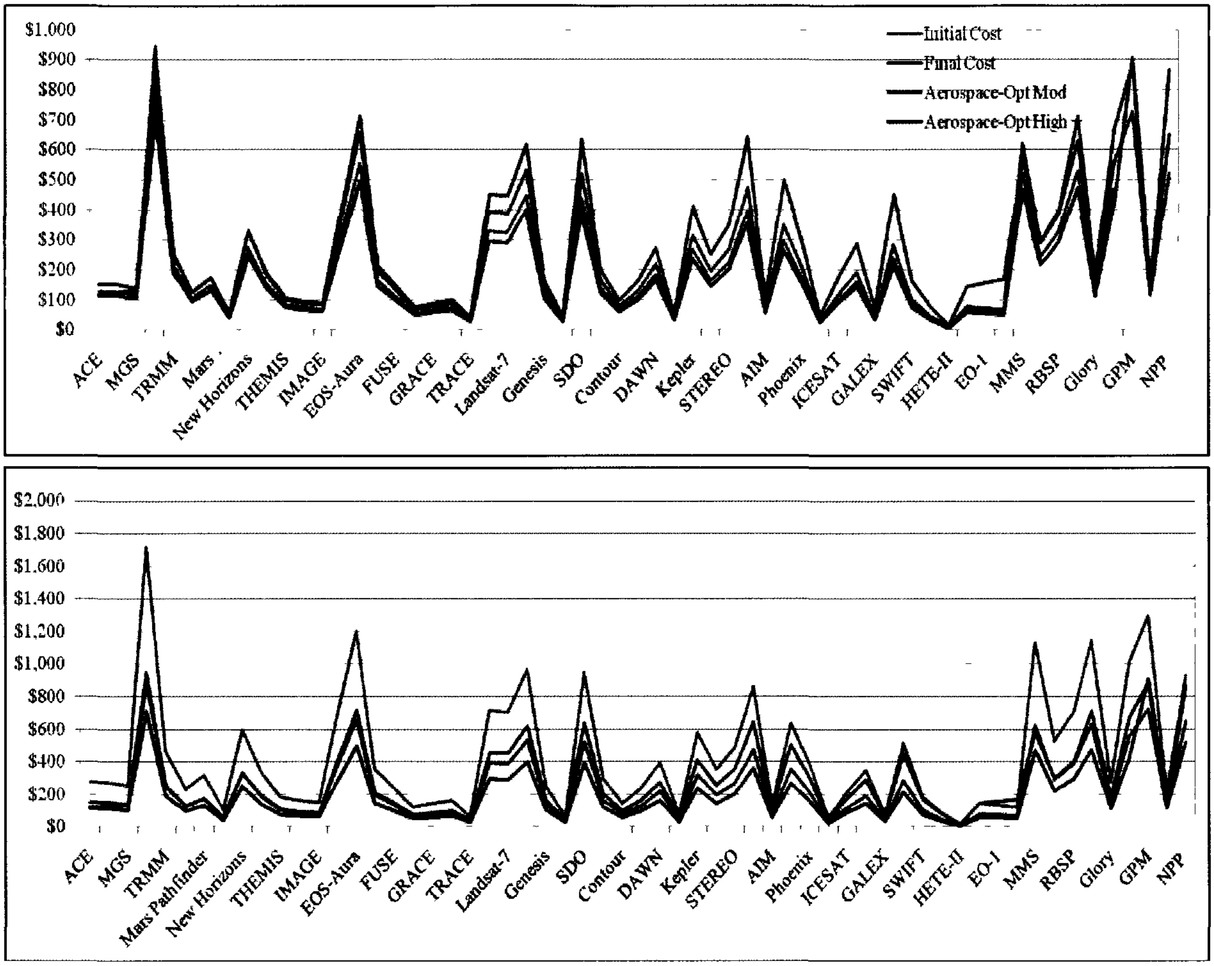


Figure 20. Aerospace Optimistic & Pessimistic Uncertainty Factors & NASA Historical Missions Data

Figure 21 displays the NASA history data and applies the BAH optimistic and pessimistic uncertainty factors for optimistic and pessimistic. As seen from the figure, these factors do not come close to the actual NASA data. Similar observations have been noticed for the BAH factors. For the pessimistic case, they overestimated the NASA cost growth missions, but the optimistic was close to the actual, except for a few missions. The high risk factors do not estimate or predict NASA actual cost estimation.

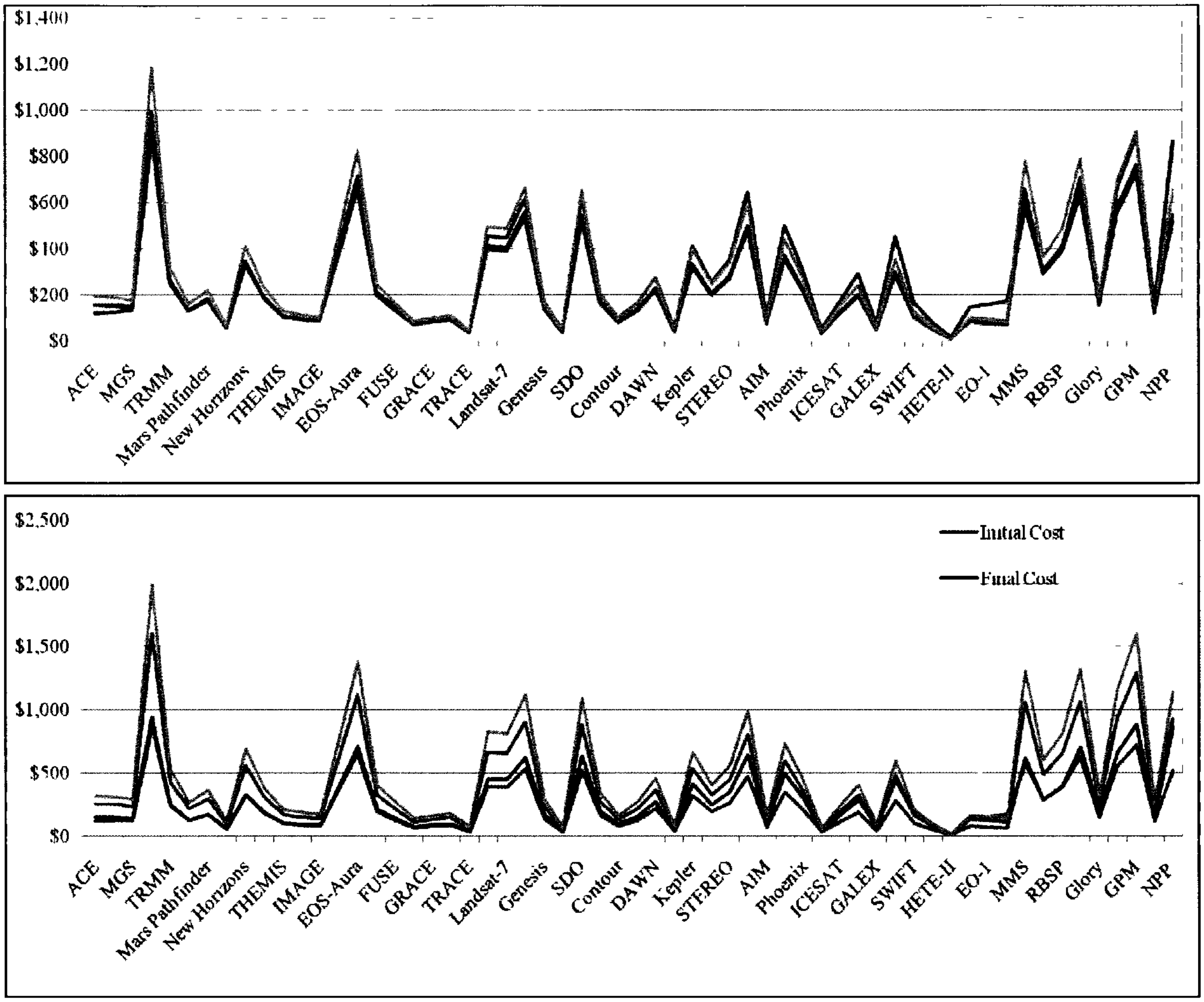


Figure 21. Booz Allen Hamilton Optimistic & Pessimistic Uncertainty Factors & NASA Historical Missions Data

Thus, the above figures demonstrate that the Air Force, Aerospace and BAH uncertainty factors are not the best tools to use to estimate or predict NASA missions' cost risks. It seems clear that no one uncertainty factor can predict the NASA missions and assess cost risk in projects. To have a useful and credible cost risk analysis, uncertainty factors must be used which fit the level of detail required and the resources available for NASA projects. Thus, NASA historical data will be of great value in developing actual NUFs.

3.6 Understanding the NASA Patterns

Traditionally, cost uncertainty is communicated through probability distributions, the results of a Monte Carlo simulation that are presented through a probable density function (PDF) or a cumulative distribution function (CDF). These methods provide the decision-maker with the probability distribution of the confidence of an estimate. Often, decision-makers are not trained or current in probability methods; thus, their understanding of the implied cost uncertainty may be limited.

NASA historical data for the sixty missions were analyzed in different matters to understand the pattern of cost growth. Figure 22 shows how most of the projects have cost growth in a range from 30-36%. Additionally, the data was sorted by chronological order to provide any indication of whether NASA is improving in cost estimating.

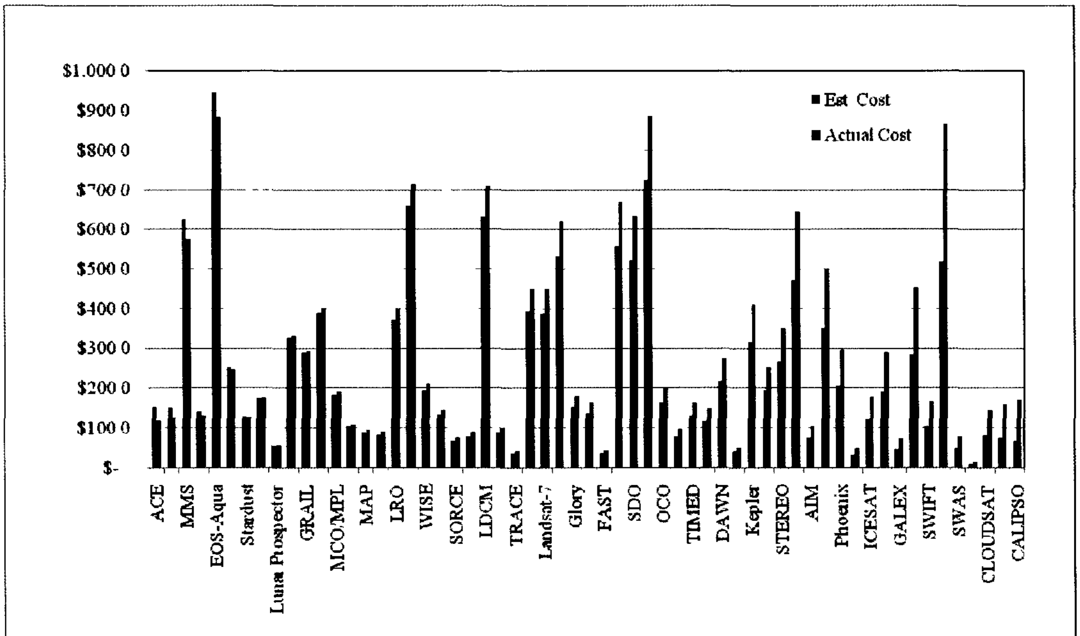


Figure 22. 60 NASA Historical Data including Initial and Actual Cost

Further analysis has been conducted to group the missions and to understand the data. Figure 23 shows four different binnings of the cost growth of NASA missions. It seems that most of the cost growth occurs between 10-30%. Over 50% of the data fall in that range, thus placing the data into bins helps the analysis and provides a manageable group data.

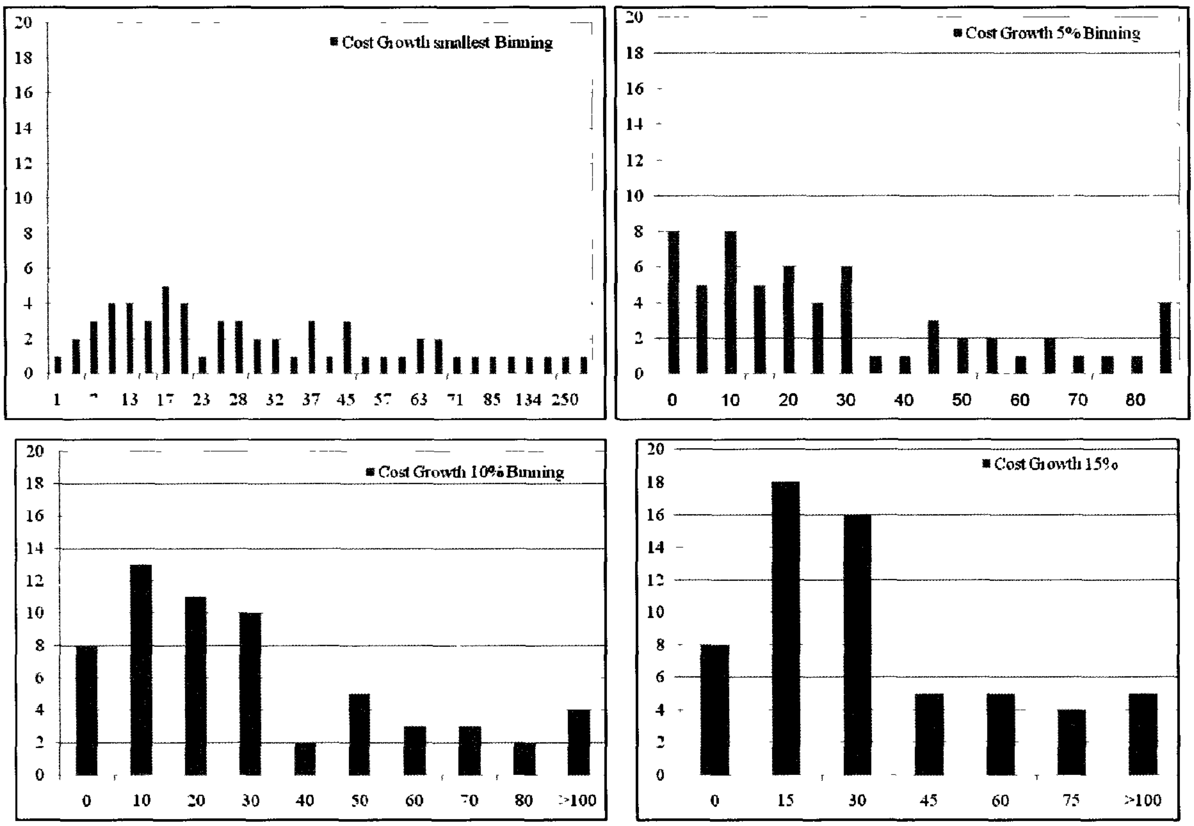


Figure 23. NASA Historical Cost Data with Size of Growth Binning

It has been selected 10% binning of the data to develop a distribution fit to the collected cost growth for fifty completed missions and ten active missions. Additionally, the collected data that is higher than 70% cost growth is grouped as one for ease of analysis (Figure 23).

3.7 Development of Distribution

This section addresses the development of a specific distribution from the NASA sixty missions cost growth data. There is a large number of possible distribution shapes defined in the literature, which are available through a variety of tools. In an effort to ensure the quality of the result, several distributions defined in Table 8 have been tested. Additionally, several software tools have been evaluated to conduct this task: Table Curve 2D, EasyFit, and Peak Fit. EasyFit was the selected software to analyze NASA data due to the fact that it was compatible with Microsoft® Excel, which is the software chosen to store the data. Additionally, EasyFit software is striving for a good balance between the accuracy and speed of calculations. It uses the Method of Moments (MOM) and the Maximum Likelihood Estimation (MLE). Moreover, it is a part of the MathWave data analysis and simulation software that has been in use for decades. Schittkowski (1998) has developed a paper explaining the EasyFit software system for data fitting in dynamic systems.

Project cost is an uncertain quantity and probability distributions are used. Triangular, Beta, Lognormal, and Normal are probability distributions commonly used in cost estimating uncertainty analysis. Figure 24 graphically demonstrates that point estimates of individual elements using the triangular and normal distributions can be quantified as most-likely, median, mean, and mode. Perlstein, Jarvis, and Muzzuchi (2001) discuss the use of the beta distribution for quantifying cost uncertainty.

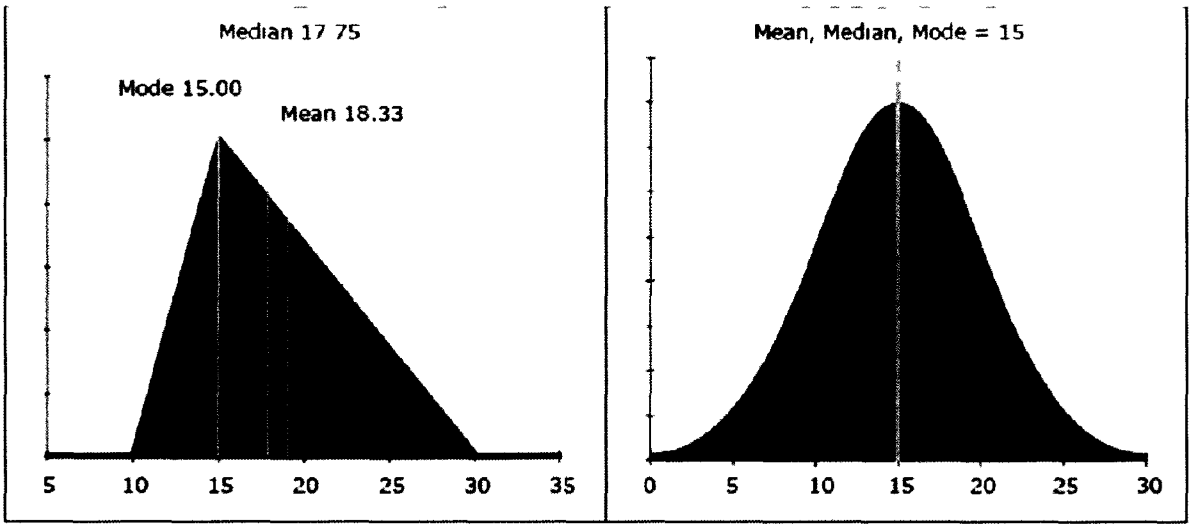


Figure 24. Statistics of the Triangular and Normal Distributions (NASA CEH, 2008)

It is important to understand that the actual cost of a project is the cumulative effect of small influences. When these influences are additive, use of the normal distribution is justified by the Central Limit Theorem (CLT). The CLT states that "the average of the sum of a large number of independent, identically distributed random variables with finite means and variances converges "in distribution" to a normal random variable" (see Figure 25). When the influences are multiplicative, use of the lognormal distribution is justified. In general, costs tend to accrue in a multiplicative sort of way, for example, wage rate multiplied by headcount. In this investigation, the normal, lognormal and other distributions commonly used in cost estimating uncertainty analysis were tested as best-fits for observed cost growth on many NASA projects. A list of most common probability used in cost estimating uncertainty analysis (shown in Table 8 from the GAO 09-3SP report) was evaluated.

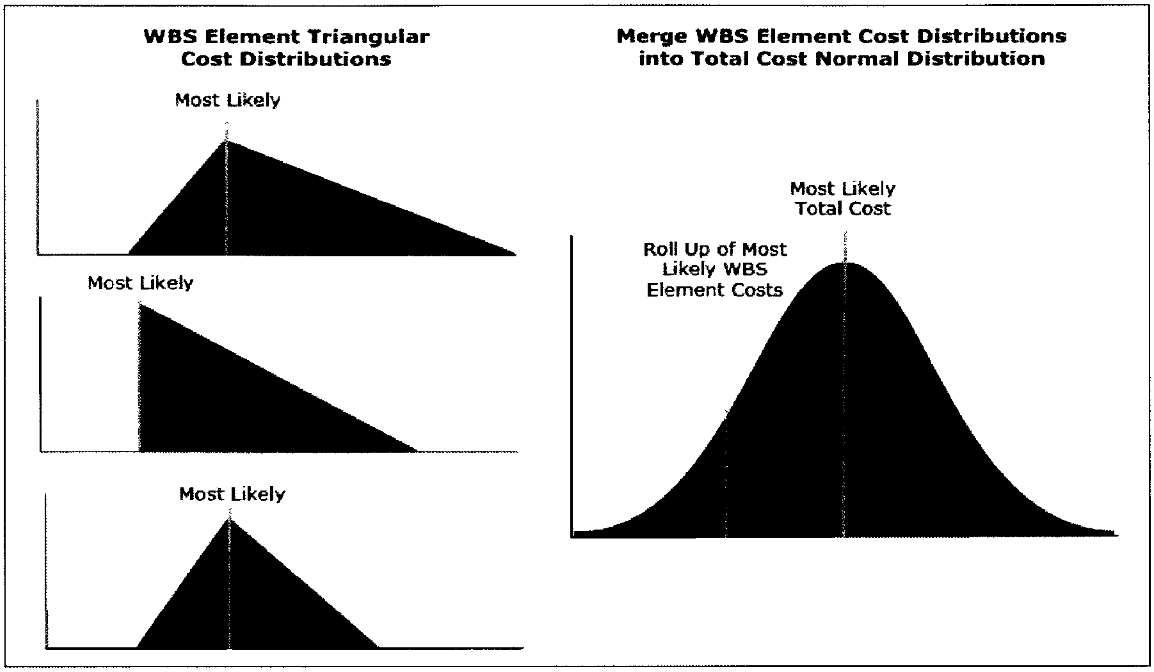
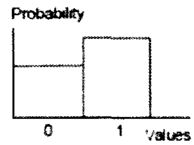
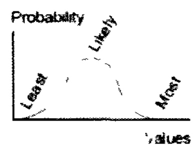
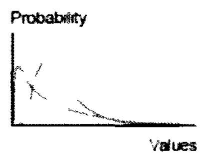
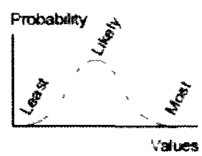
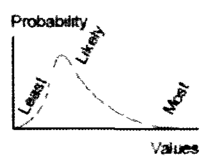
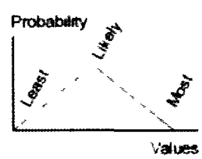
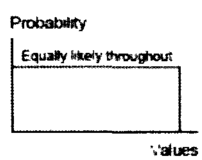
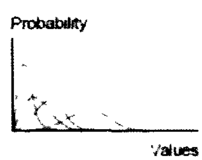


Figure 25. Central Limit Theorem (NASA CEH, 2008)

Table 8. Common Probability Distributions (GAO 09-3SP Report, 2009)

Distribution	Description	Shape	Typical application
Bernoulli	Assigns probabilities of "p" for success and "1 - p" for failure; mean = "p"; variance = "1 - p"		With likelihood and consequence risk cube models; good for representing the probability of a risk occurring but not for the impact on the program
Beta	Similar to normal distribution but does not allow for negative cost or duration, this continuous distribution can be symmetric or skewed		To capture outcomes biased toward the tail ends of a range; often used with engineering data or analogy estimates; the shape parameters usually cannot be collected from interviewees
Lognormal	A continuous distribution positively skewed with a limitless upper bound and known lower bound; skewed to the right to reflect the tendency toward higher cost		To characterize uncertainty in nonlinear cost estimating relationships; it is important to know how to scale the standard deviation, which is needed for this distribution
Normal	Used for outcomes likely to occur on either side of the average value; symmetric and continuous, allowing for negative costs and durations. In a normal distribution, about 68% of the values fall within one standard deviation of the mean		To assess uncertainty with cost estimating methods; standard deviation or standard error of the estimate is used to determine dispersion. Since data must be symmetrical, it is not as useful for defining risk, which is usually asymmetrical, but can be useful for scaling estimating error
Poisson	Peaks early and has a long tail compared to other distributions		To predict all kinds of outcomes, like the number of software defects or test failures
Triangular	Characterized by three points (most likely, pessimistic, and optimistic values), can be skewed or symmetric and is easy to understand because it is intuitive; one drawback is the absoluteness of the end points, although this is not a limitation in practice since it is used in a simulation		To express technical uncertainty, because it works for any system architecture or design; also used to determine schedule uncertainty
Uniform	Has no peaks because all values, including highest and lowest possible values, are equally likely		With engineering data or analogy estimates
Weibull	Versatile, can take on the characteristics of other distributions, based on the value of the shape parameter "b"—e.g., Rayleigh and exponential distributions can be derived from it[a]		In life data and reliability analysis because it can mimic other distributions and its objective relationship to reliability modeling

The most popular distribution shapes tested in this investigation with sixty NASA missions' data include: lognormal, log logistic, Weibull, Normal, Beta, Burr, and general extreme value. Figure 26 displays the sixty missions as functions of cost growth percentage plotting with PDF and the probability-probability (P-P) plot. The P-P plot is a graph of the empirical CDF values plotted against the theoretical CDF values. It is used to determine how well a specific distribution fits to the observed data. This plot will be approximately linear if the specified theoretical distribution is the correct model. These plots are used as visual and qualitative assessments.

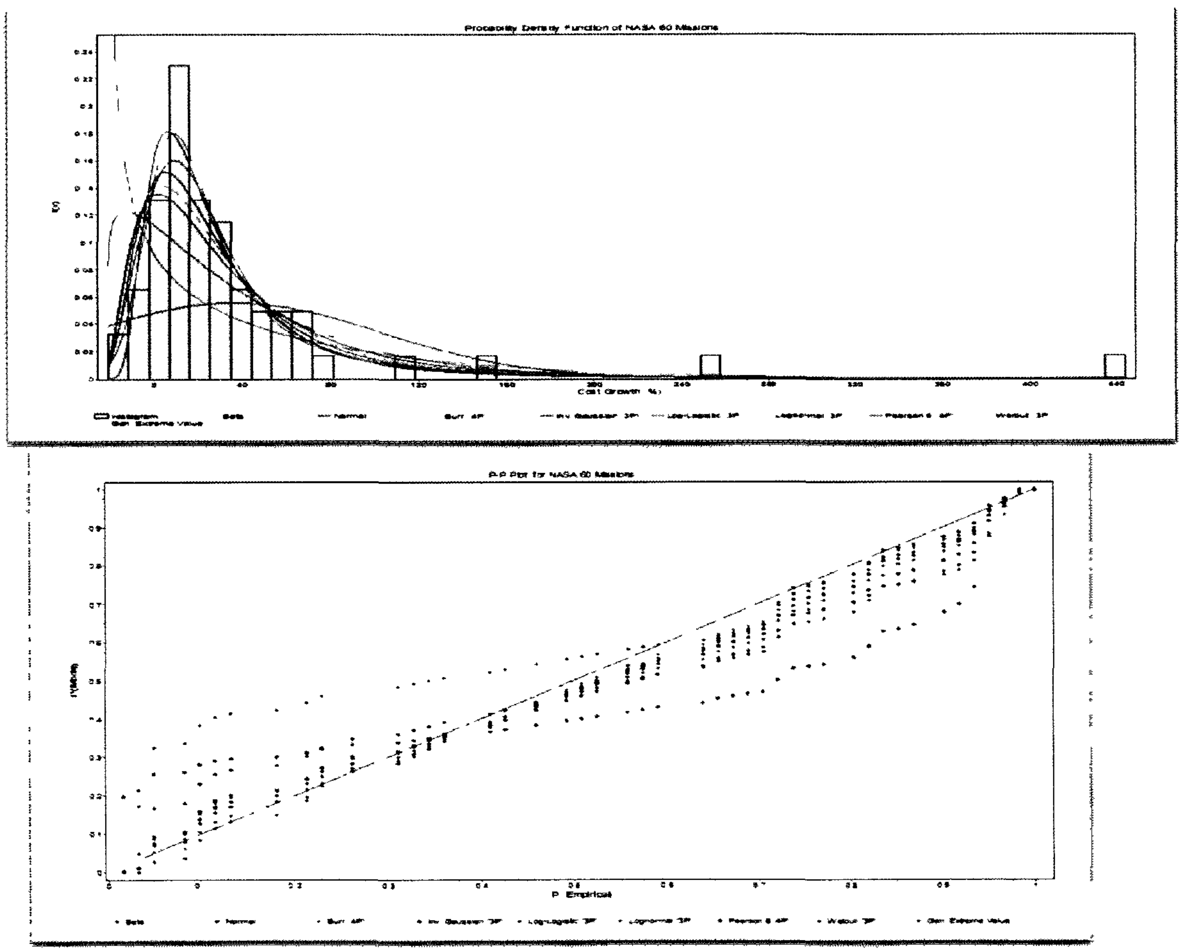


Figure 26. Probability Density Function & Probability-Probability Plot for 60 NASA Missions

Figure 26 shows that Beta, Burr, Log-Logistic and lognormal distributions fit the data well. Table 9 displays the summary of the distribution parameters.

Table 9. 60 Missions Data Fits

Distribution	Parameters
Beta	α_1=0.54859 α_2=4.1218 a=-21.0 b=444.0
Burr (4P)	k=0.42648 α=5.87 β=49.091 γ=-42.854
Gen. Extreme Value	k=0.37931 σ=20.12 μ=12.455
Inv. Gaussian (3P)	λ=128.48 μ=66.62 γ=-30.636
Log-Logistic (3P)	α=2.8108 β=46.552 γ=-26.488
Lognormal (3P)	σ=0.66093 μ=3.9014 γ=-28.101
Normal	σ=67.06 μ=35.984
Pearson 6 (4P)	α_1=878.35 α_2=4.143 β=0.25804 γ=-38.756
Weibull (3P)	α=1.1225 β=59.975 γ=-21.142

Several tests from the EasyFit software test the quality of the fit of two tests: the Kolmogorov-test and the Anderson-Darling test. The Kolmogorov-Smirnov statistic (D) is based on the largest vertical difference between the theoretical and the empirical cumulative distribution function. The Anderson-Darling procedure is a general test to compare the fit of an observed cumulative distribution function to an expected cumulative distribution function. This test gives more weight to the tails than the Kolmogorov-Smirnov test. Appendix G has the summary for all the cases that have been tested for this project.

Figure 27 shows the cost growth data for only fifty-four NASA missions, which do not include under cost missions. Table 10 displays the result of the distribution fits.

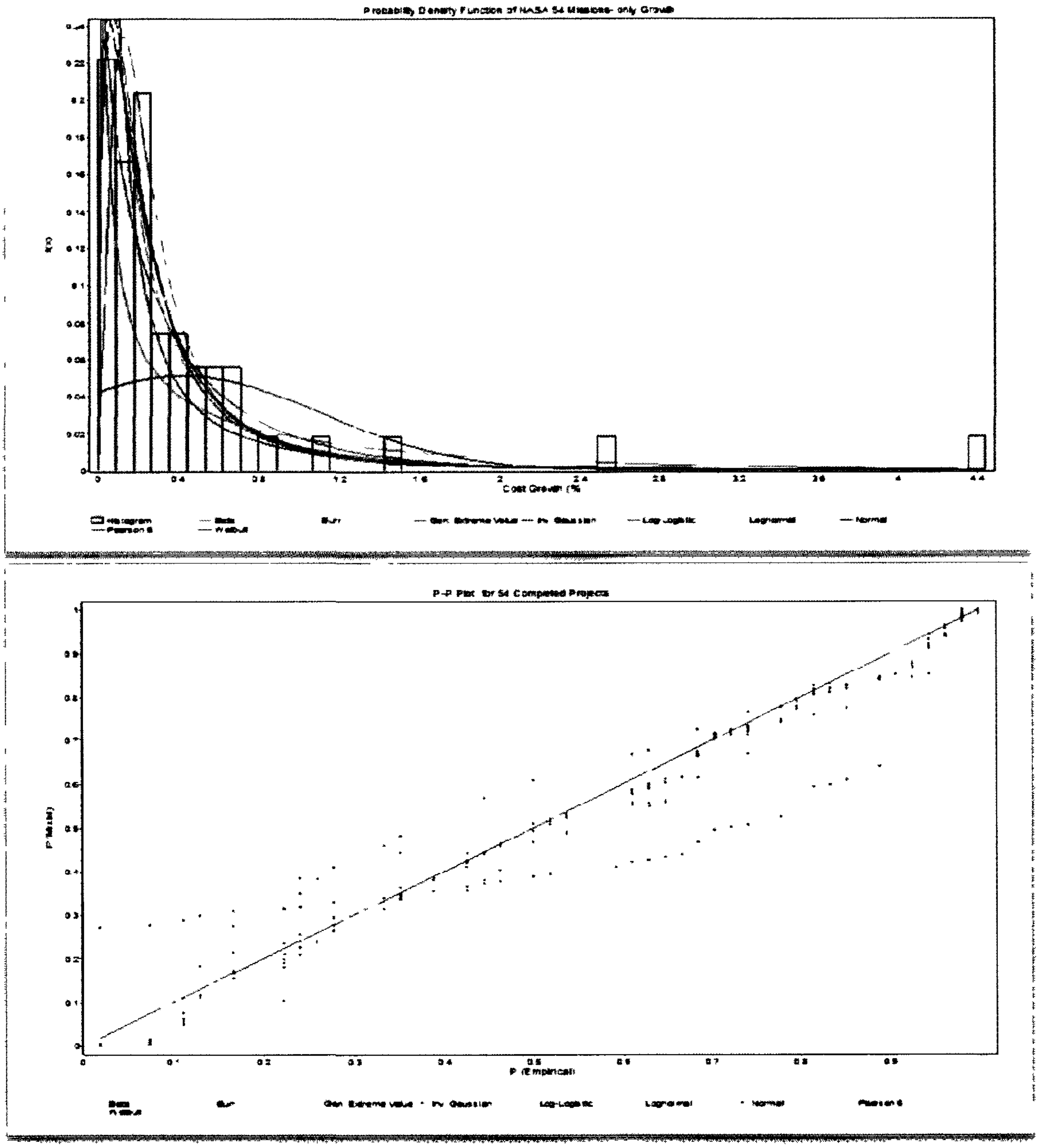


Figure 27. Probability Density Function & Probability-Probability Plot for 54 NASA Missions

Table 10. Summary for the 54 Mission Quality of the Fit

Distribution	Parameters
Beta	α_1=0.3319 α_2=2.789 a=-6.2932E-17 b=5.4851
Burr	k=1.5284 α=1.3144 β=0.34407
Gen. Extreme Value	k=0.49034 σ=0.15481 μ=0.1848 4
Inv. Gaussian	λ=0.15329 μ=0.41833
Log-Logistic	α=1.4856 β=0.22092
Lognormal	σ=1.238 μ=-1.5616
Normal	σ=0.69109 μ=0.41833
Pearson 6	α_1=1.4119 α_2=2.4747 β=0.43966
Weibull	α=0.84335 β=0.38227

The data presented in the three tables above lead to narrowing the focus of Weibull and lognormal distributions. Several other runs have been conducted to understand the actual behavior of the data, as follows:

1. Delete two missions that are over 150% cost increase (see Figure 28). They may be outlier missions within the data set. Outliers were checked by determining if the fit got better by not including any one mission in the data set at a time.

2. Include only increase cost - Delete under-cost missions and two missions above (see Figure 29).

3. Delete missions over 100% cost growth (see Figure 30).

4. Concentrate on the two distributions: lognormal and Weibull (see Figure 31).

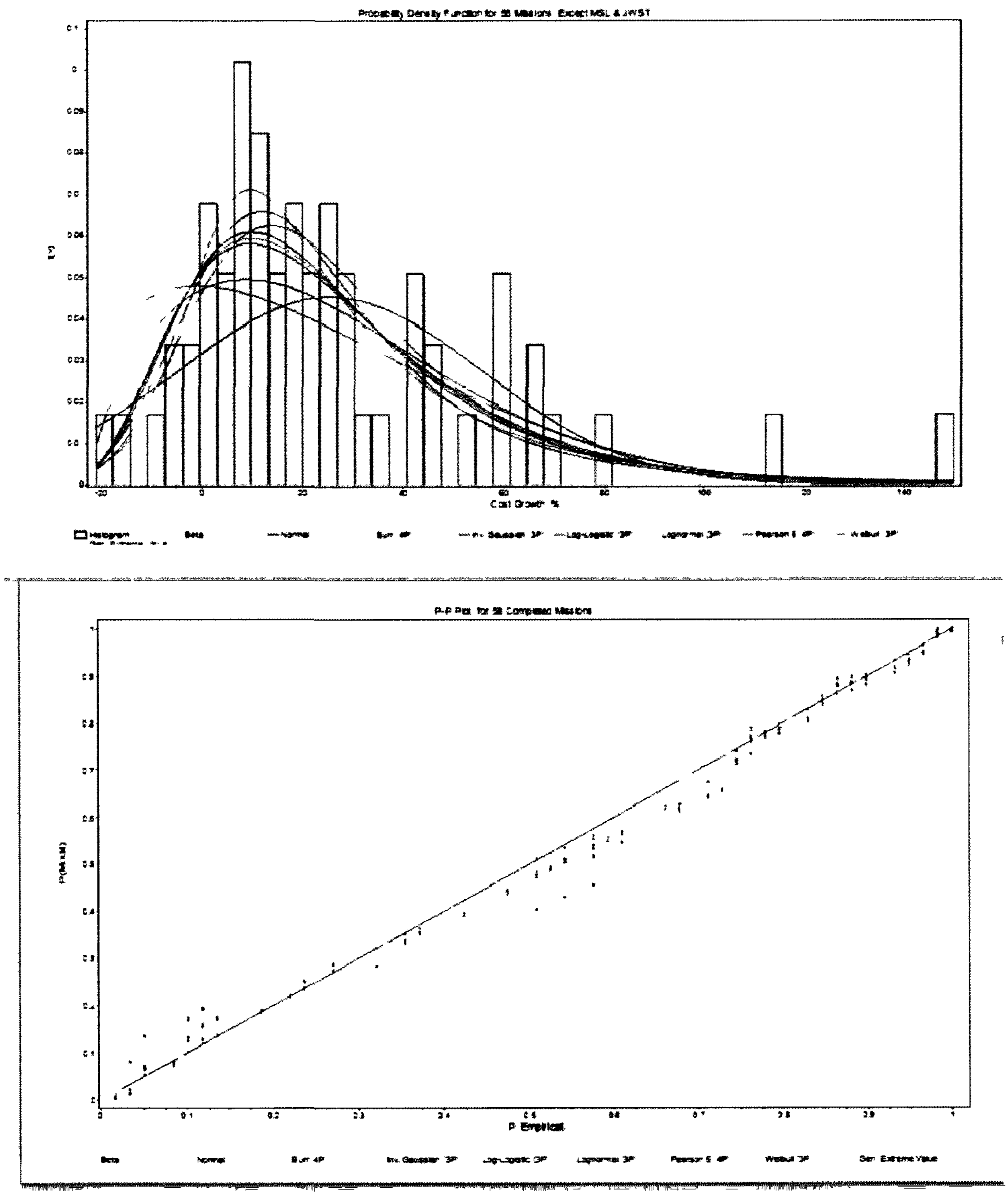


Figure 28. Probability Density Function & Probability-Probability Plot for 58 NASA Missions

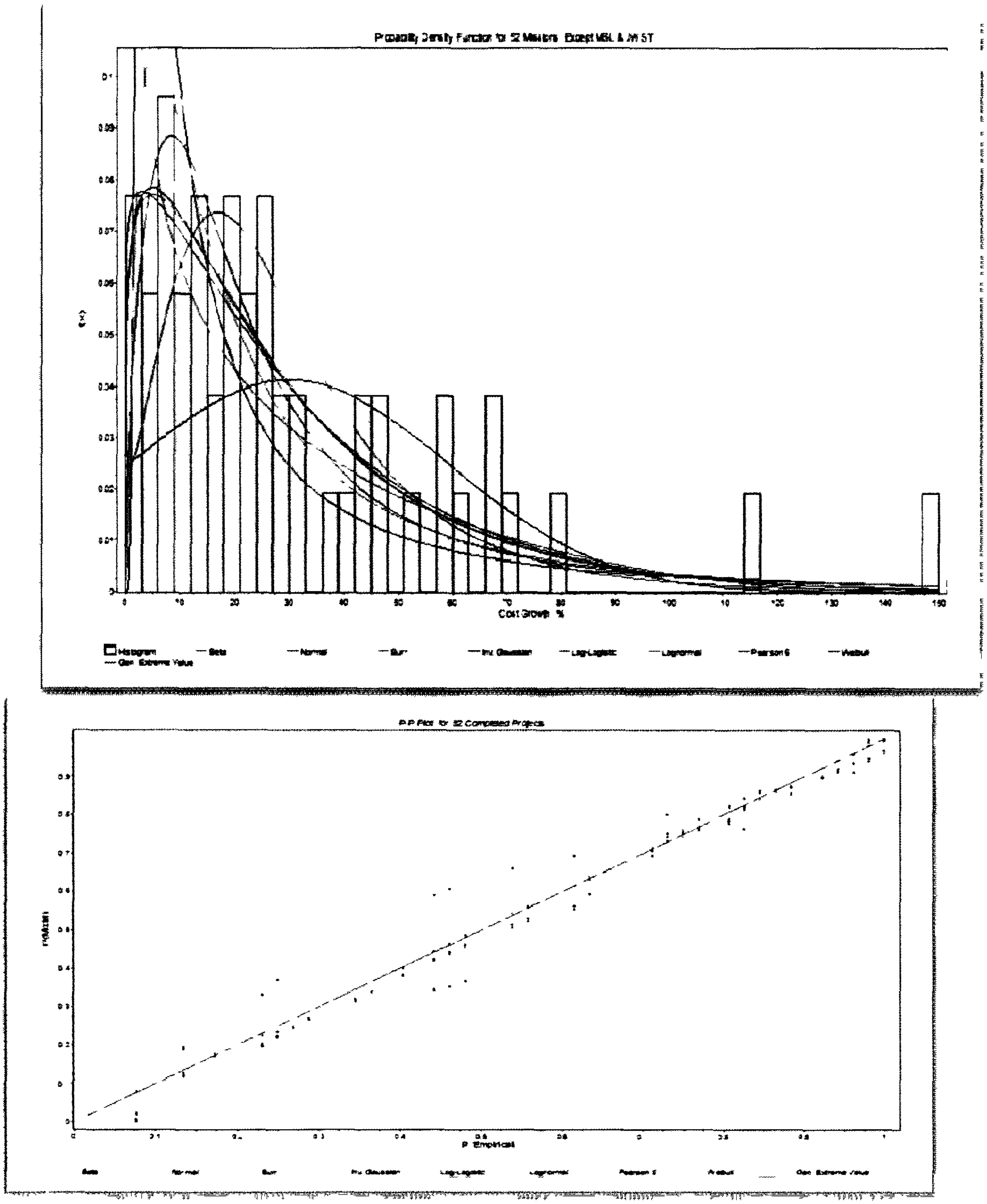


Figure 29. Probability Density Function & Probability-Probability Plot for 52 NASA Missions

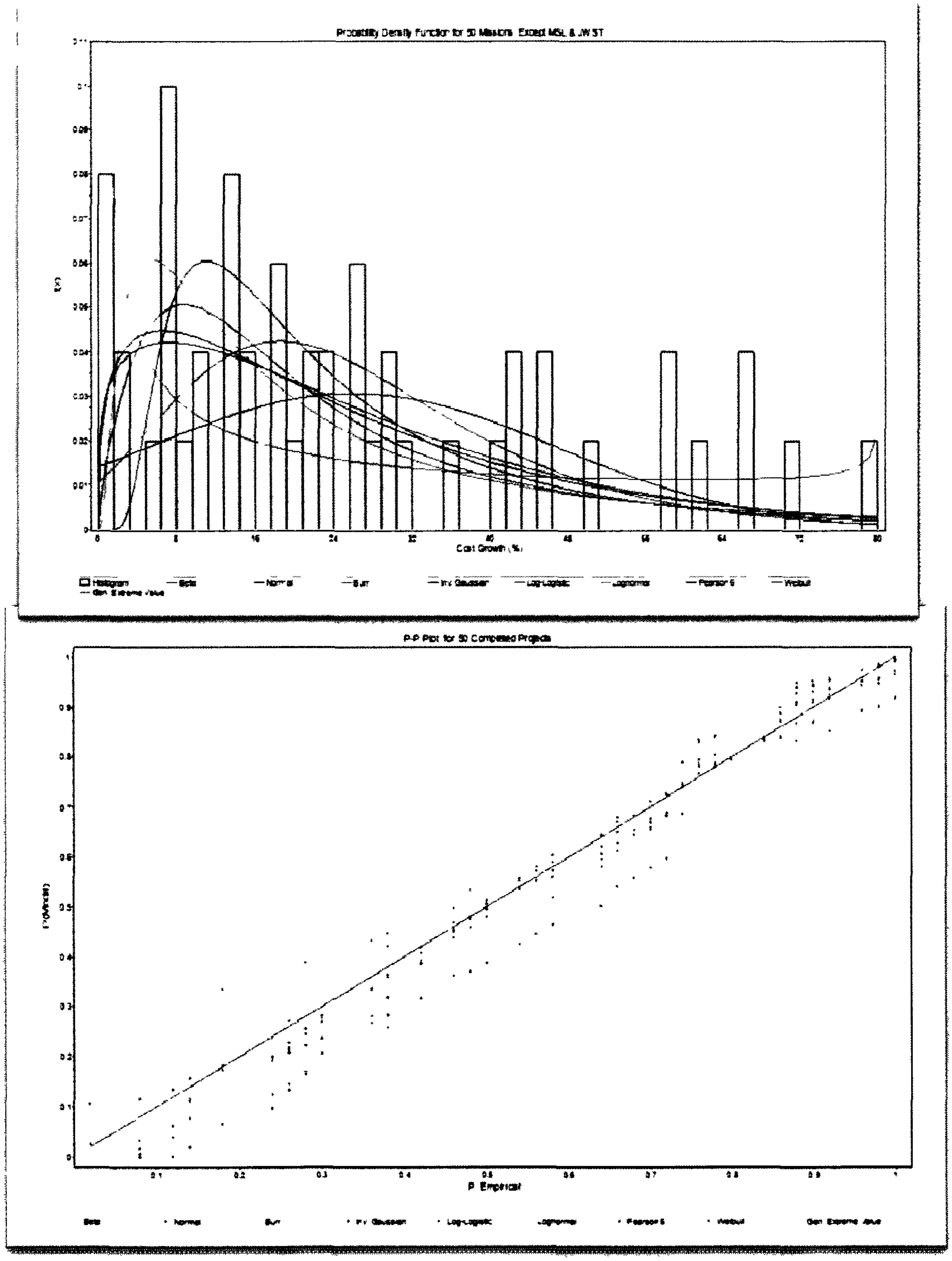


Figure 30. Probability Density Function & Probability-Probability Plot for NASA Missions less 100% Cost Growth

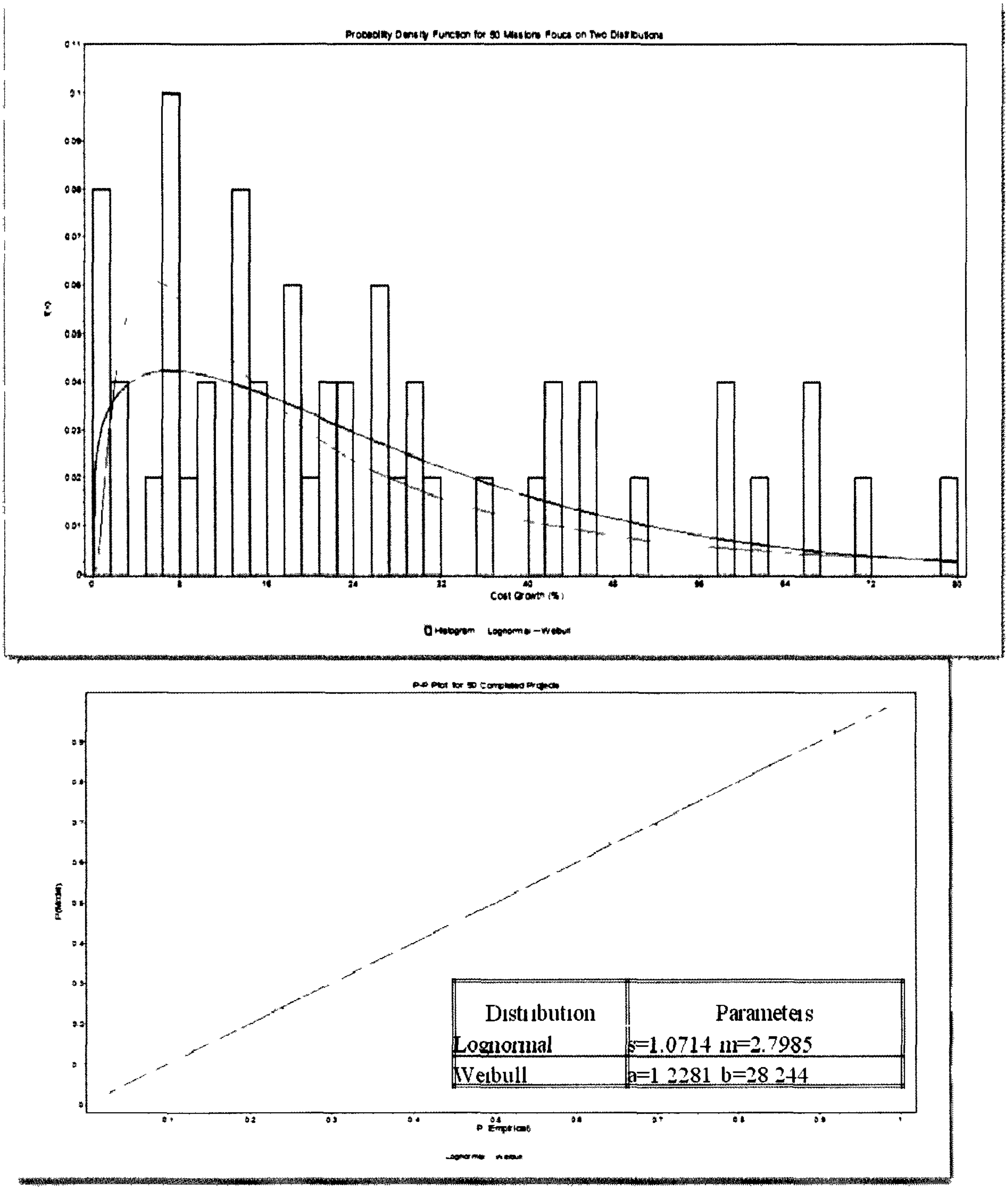


Figure 31. Probability Density Function & Probability-Probability Plot for 50 NASA Missions –Focus on Two Distributions with Less 100% Cost Growth

Numerous studies have empirically shown the lognormal and Weibull to be excellent approximations to the overall distribution function of a mission's total cost, even in the presence of correlations among cost element costs. The lognormal is similar to the Weibull, but lognormal is different than the Weibull distribution because it is skewed towards the positive end of the range and captures more of the initial missions in the lower cost growth instead of being flat in the beginning of the distribution. The lognormal distribution illustrates the distribution shape if the cost growth bounds are taken as "10-30%," which seems normal for most missions (see Figure 32). The three-parameter lognormal distribution is:

σ- continuous parameter(α>0)

μ- continuous parameter

γ - continuous location parameter ($\gamma \equiv 0$ yields the two-parameter lognormal distribution)

Domain $\gamma < x < +\infty$

- Probability Density Function

$$F(X)= \exp (-1/2 (\ln (x- \gamma)- \mu / \sigma)^2)/ (x- \gamma) \sigma (2\pi)^{1/2}$$

- Cumulative Distribution Function

$$F(x) = \varphi (\ln (x- \gamma)- \mu/ \sigma) \quad \varphi \text{ is the Laplace Integral}$$

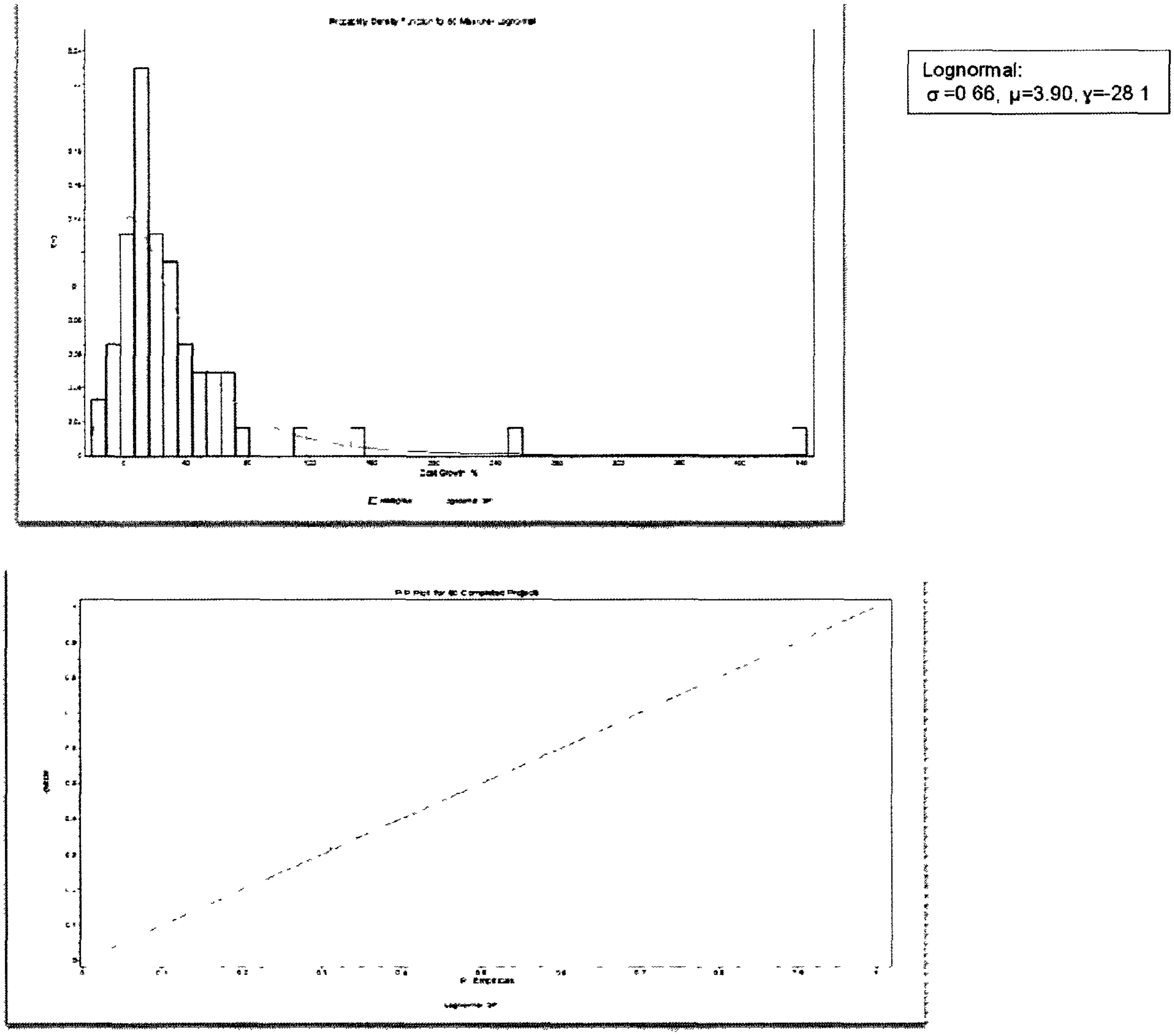


Figure 32. Probability Density Function & Probability-Probability Plot for 60 NASA Missions –Focus on Lognormal Distributions

Galton (1879) stated that the lognormal is used when considering the multiplication or the geometric mean for independent random variables, and the CLT applies to their logarithms. The lognormal distribution shape is selected distribution that is ultimately modeled in the analysis and has the following property: mean of 3.03 and standard deviation of 1.08. This distribution is based on the 44 completed missions with cost growth only. Thus, this lognormal distribution has been selected to describe the NASA historical data distribution (see Figure 33):

$$F(X) = \frac{Exp\ (-1/2(\frac{lnx-\mu}{\sigma})\text{^}2)}{x\sigma(2\pi)\text{^}2}$$

μ= 3.03

σ= 1.08

The parameters denoted μ and σ are the mean and standard deviation, respectively, of the variable's natural logarithm. Additionally, those parameters that can be converted to normal μ and σ, are the mean and standard deviation, respectively, then the values are:

μ= *20.7*

σ= 2.91

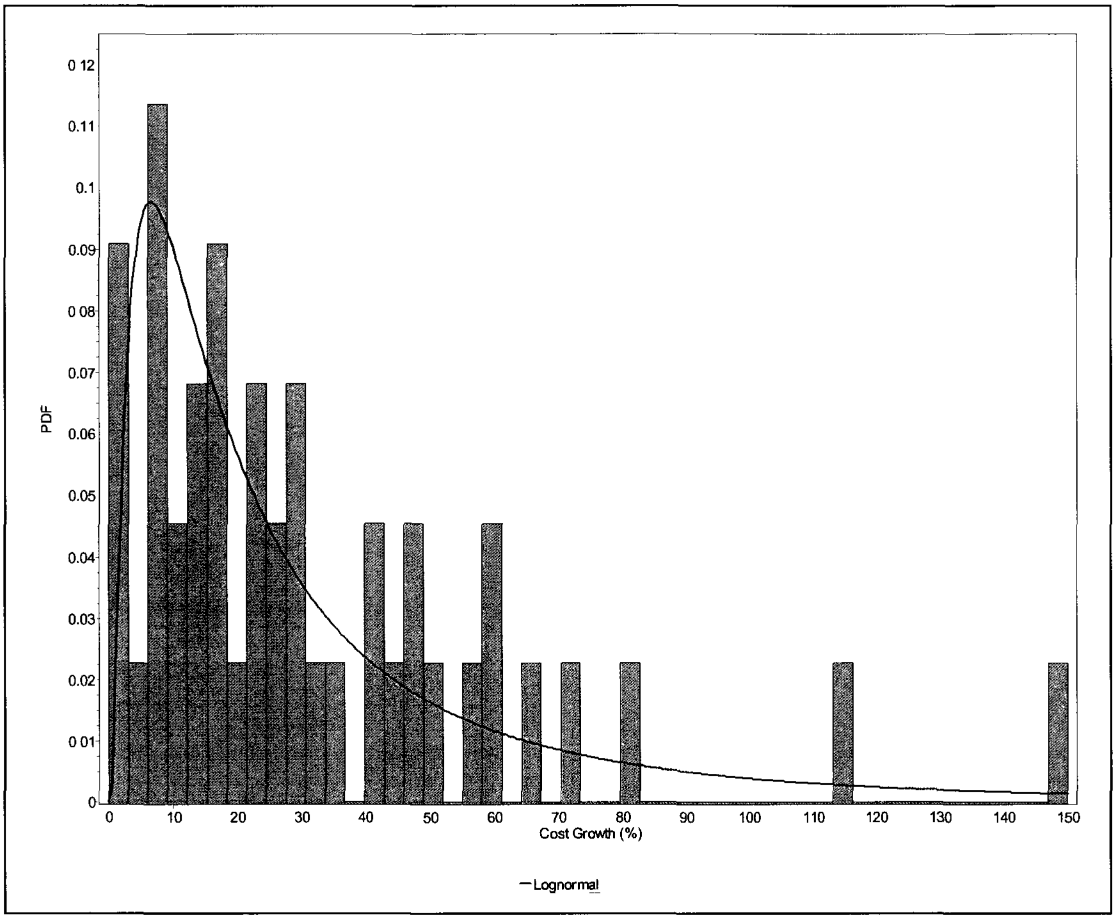


Figure 33. Probability Density Function for 44 NASA Missions –Focus on Lognormal Distribution and its Property

Several runs have been conducted to test the robustness of the selected distribution. Below are four lognormal distributions from three NASA cost data sets:

1. All data including MSL and JWST (A- Data), 54 missions (Figure 34).

2. All data excluding MSL and JWST (B- Data), 52 missions (Figure 35).

3. All completed missions (C-Data), 44 missions (Figure 33).

4. All data less than 100% cost growth (D- Data).

Table 11. Four Lognormal Distributions Properties for NASA Data

Type of Data	σ= Mean	% Error	μ =Std. Dev.	% Error
A - Data	1.18	6	3.01	3.08
B - Data	1.11	2.78	2.92	3.63
C - Data	1.08	0.9	3.03	6.32
D-Data	1.07		2.85	

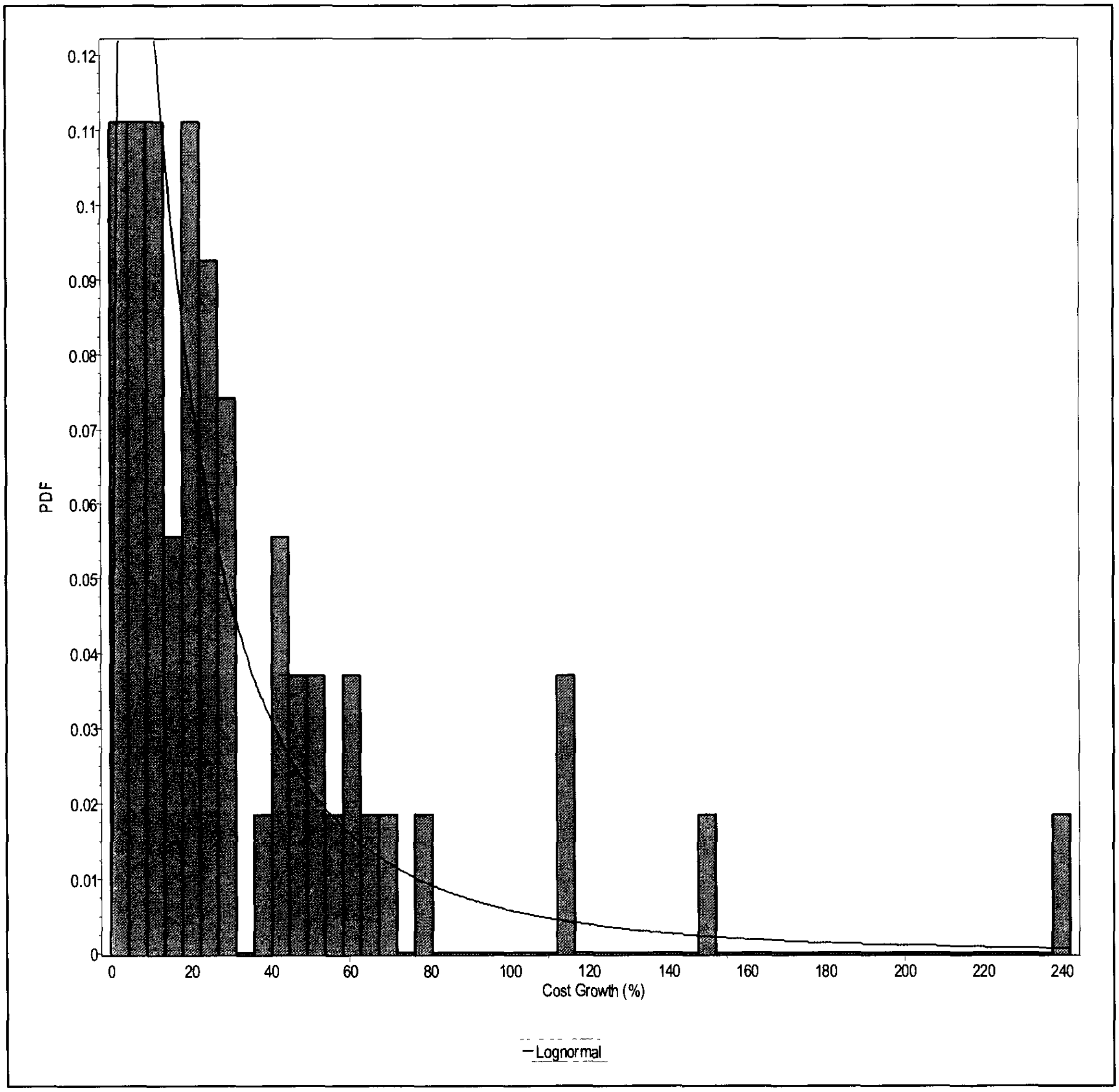


Figure 34. Probability Density Function for 54 NASA Missions

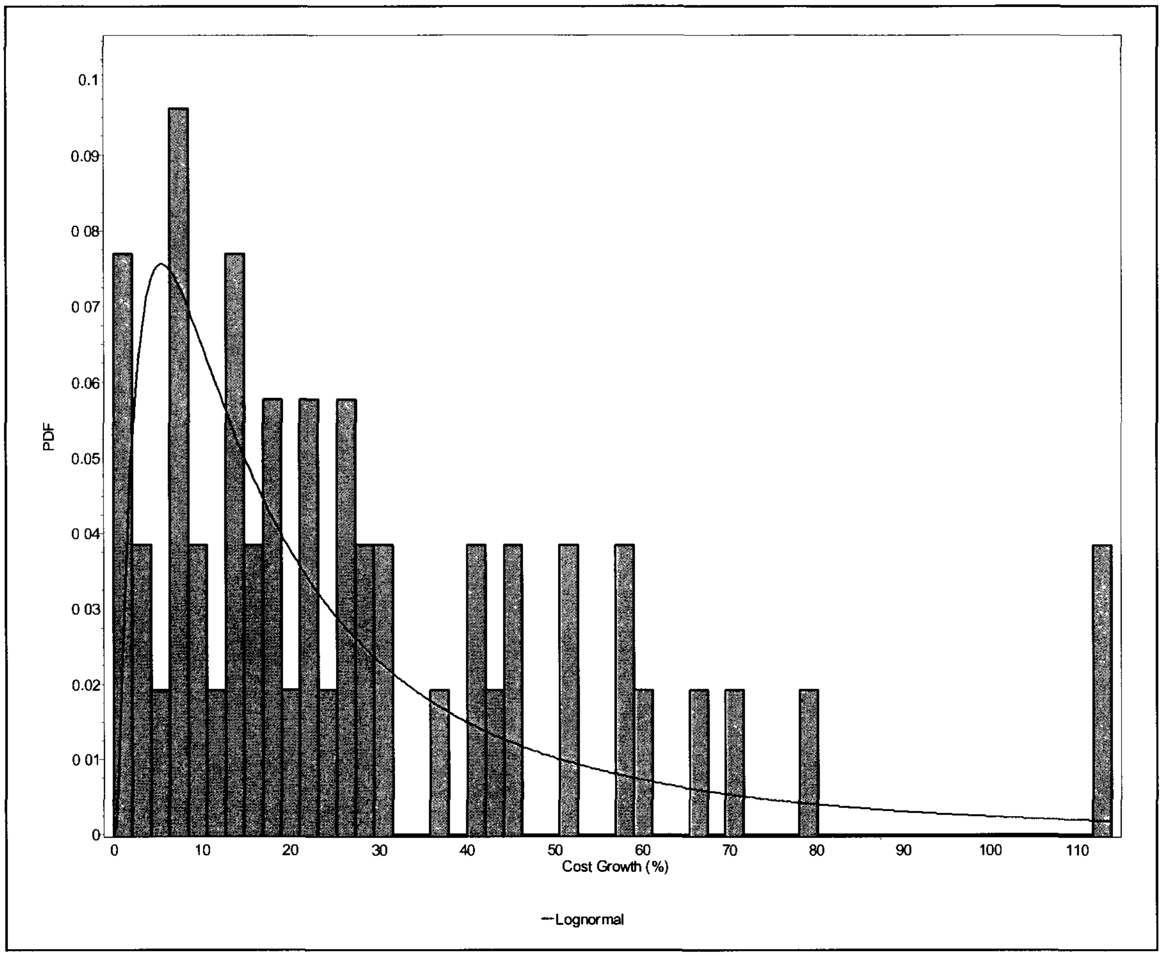


Figure 35. Probability Density Function for 52 NASA Missions

The lognormal distribution is the most suitable distribution that a cost estimator can use to perform an uncertainty analysis for the NASA data (see Appendix H for lognormal model). Lognormal distribution has a defined lower bound that is never less than zero and an upper bound of infinity, which provides at least some probability of a large cost overrun, as seen in several missions. It is sufficient and represents the characteristic of the NASA historical data. Dataset C and Figure 33 are the recommended data to represent NASA historical data and will be used to develop the NUFs.

CHAPTER 4

RESULTS AND DISCUSSION

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[illegible]

This chapter provides an overview of the development of the NUF and the validation of these factors with NASA data. NUF begins with a general understanding of the lognormal property, and then specifically addresses the factors with validation of several missions.

4.1 Development of NASA Uncertainty Factors

One of the major considerations in cost estimating is how to assess and quantify technical, cost, and schedule risks. Certainly, there are many complex methods and formulas that do so, but these risks are ultimately subjective and judgmental in nature, no matter how they are developed and applied. The intent of this project is to provide a means and rationale for estimating mission risk using a common-sense, non-statistical approach that generates results using historical data that correlate well with more mathematically rigorous methods.

Uncertainty is expressed in a simulation by specifying the shape and bounds of the uncertainty distribution for the cost methods and cost drivers (input variables) where the value is not certain. Understanding the NASA data distribution could be used as a lognormal distribution model from the previous chapter. Lognormal distributions have a defined lower bound that is never less than zero. Lognormal does not permit a negative tail and preserves the mean and standard deviation. They have an upper bound of infinity, thus providing at least some probability of a large cost overrun. The skew of a lognormal is pre-defined.

The development of the uncertainty factors from NASA data will now be developed and demonstrated. Graphing the lognormal distribution with NASA data in a Q-Q plot, 85% of data has shown falls in a normalized line in the 0-30% range. Figure 36 shows the NASA data is mostly below 40% cost growth. Additionally, there are four data points that cover missions with cost growth over 100% that do not lie within the Q-Q plot. These missions are outside the normal NASA historical cost growth and could be skewing the plot, but they needed to be included. The statistical analysis of the historical data to derive the growth uncertainty factor is straightforward. It has the additional advantage that it takes into account the trends in costs that are not explicitly used in the historical analogy methodology.

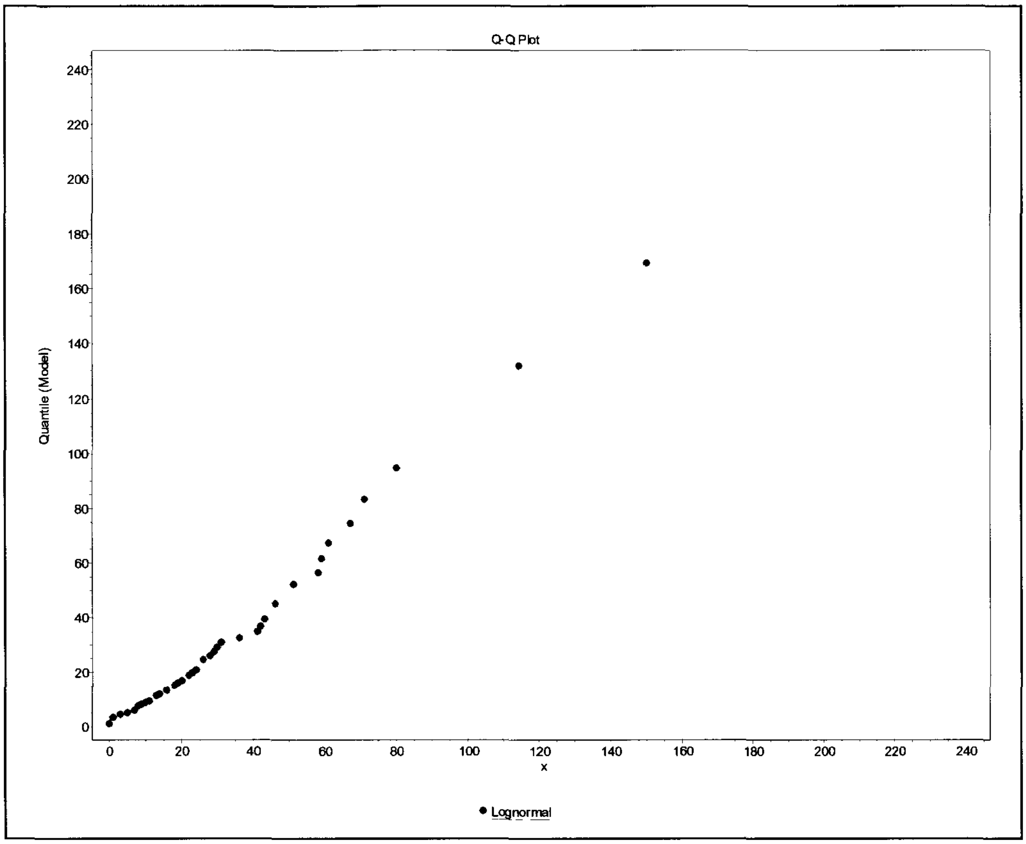

Figure 36. Q-Q Plot of the 54 NASA Missions – Focus on Lognormal Distribution

If one concentrates on the completed missions mentioned above, then focus on the actual repeated cost growth can be recommended for more realistic uncertainty factors. Figure 37 shows the Q-Q plot for a mission that has cost growth less than 100%. The quantile-quantile (Q-Q) plot is a graph of the input (observed) data values plotted against the theoretical (fitted) distribution quantiles. Both axes of this graph are in units of the input data set. For this data set, the qualitative review suggests that the data is consistent with the theoretical fit, except for the two data points with high cost growth.

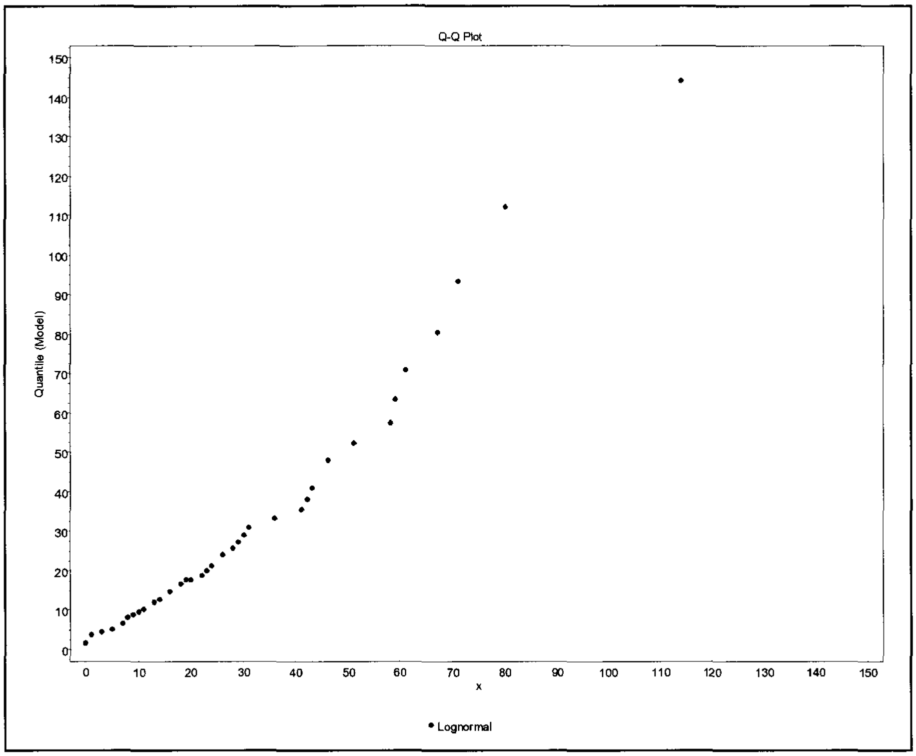

Figure 37. Q-Q Plot for 44 NASA Completed Missions

Table 12 provides the recommended NUF based on the historical data. This table consists of four types of uncertainty factors: risk not adjusted, conservative, semi-aggressive, and aggressive. These factors correspond to three levels of risk: moderate, high, and very high. The moderate level of risk is defined as between 10-30% based on the data. Additionally, a 30% limit is set because a report to Congress is necessary above this level. The high and high plus risk are defined based on the complexity of the missions and technology development. They range from 30-70% growth for high and higher than 250% for very high.

Table 12. Recommended NASA Uncertainty Factors (NUFs)

Level of Risk	*NASA Uncertainty Factors*			
	No- Risk Adjusted	Conservative	Semi-Aggressive	Aggressive
Moderate (10-30%)	1	1.1	1.2	1.3
High (30-75%)	1	1.3	1.5	1.75
Very High (>75%)	1	1.75	2.1	2.5

The justification for the uncertainty factors for each category is based on actual data and from the developed distribution of lognormal. Most of the data are contained in the range from conservative-to-aggressive for the moderate risk level from Table 12. NASA missions, such as Lunar Reconnaissance Orbiter (LRO), Wide-Field Infrared Survey Explorer (WISE), and Far Ultraviolet Spectroscopic Explorer (FUSE) are at a 10% moderate level risk with conservative uncertainty factors. Moreover, Dawn, Orbiting Carbon Observatory (OCO) and Wide-field Infrared Explorer (WIRE) are examples of the moderate level of risk, but with aggressive uncertainty factors.

For the high and very high risk levels, there are a wide range of factors (30-70%) based on the complexity of the missions. Figure 38 shows NASA missions plotted on the lognormal distribution to provide a clear picture of the data.

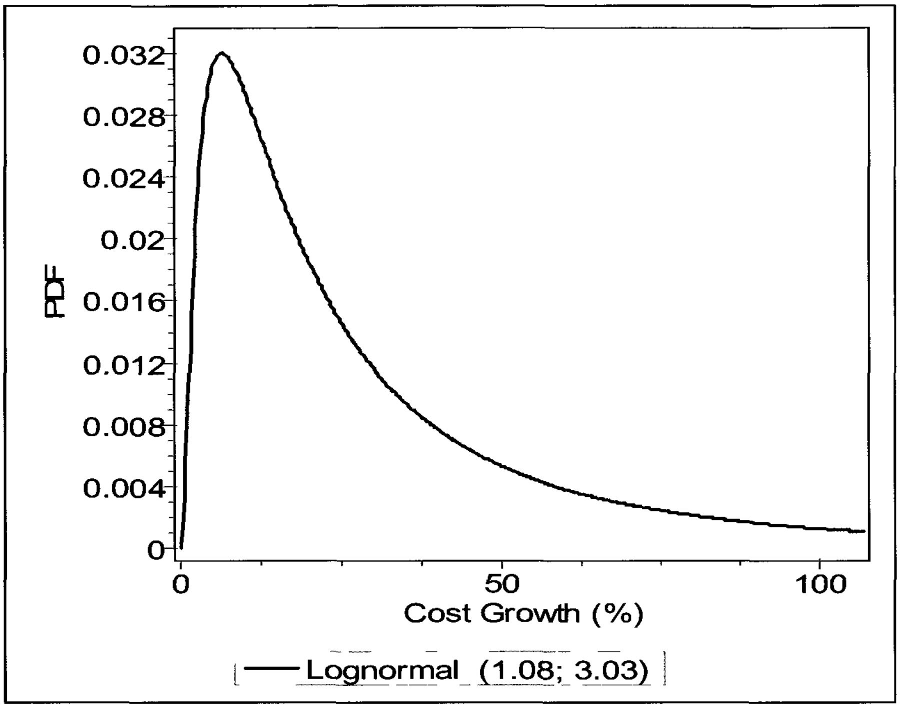

Figure 38. NASA Missions Data with NASA Developed Lognormal Distribution

The general guidelines to use the NUFs are:

- Analyst Judgment
- Mission Complexity
- Heritage Level
- Similarity of Missions

Finally, the risk factor can be changed as the mission development becomes more mature, which allows for the adjusting of the factor to predict the actual cost or cost growth. Therefore, a cost risk should not prescribe one method, but rather allow some flexibility as long as the analyst gets the information they need to justify their methodology. For example, it will be difficult to assess cost risk for a mission at an early conceptual stage (which has limited programmatic or technical definition) using the more complex methods. For such a case, simple method-using uncertainty factors might be more appropriate and still convey the relative cost risk for the mission. However, a mission going through a major milestone should have sufficient detail defined to employ a probabilistic method. Given adequate time and trained analysts, it should be feasible to use one of the more complex methods. However, if a risk assessment and estimate need to be generated very rapidly, then a simpler method must be employed.

4.2 Validation of NASA Uncertainty Factors

The first step in the validation process is the selection of the validation data points, which were the same as the NASA historical data. Using the developed uncertainty factors with NASA data to validate the quality of the factors for several risk levels, a small subset of the database was conducted and analyzed, as follows:

4.2.1 Conservative Factors

1. All data with conservative factors with and three risk levels (Figure 39).
2. Data of conservative factors and missions with moderate risk only (Figure 40).
3. Data of conservative factors with moderate risk level up to 30% cost growth (Figure 41).
4. Data of conservative factors with high risk level (Figure 42).

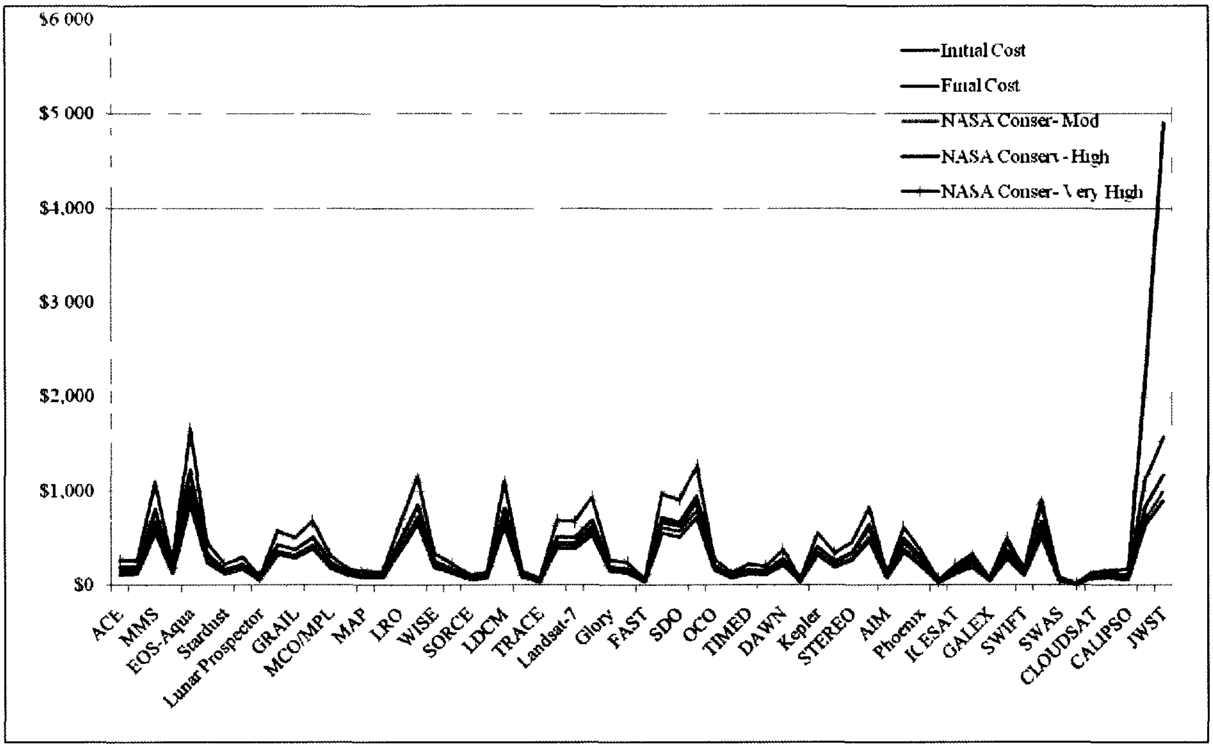

Figure 39. Applied Conservative NUC to NASA Data

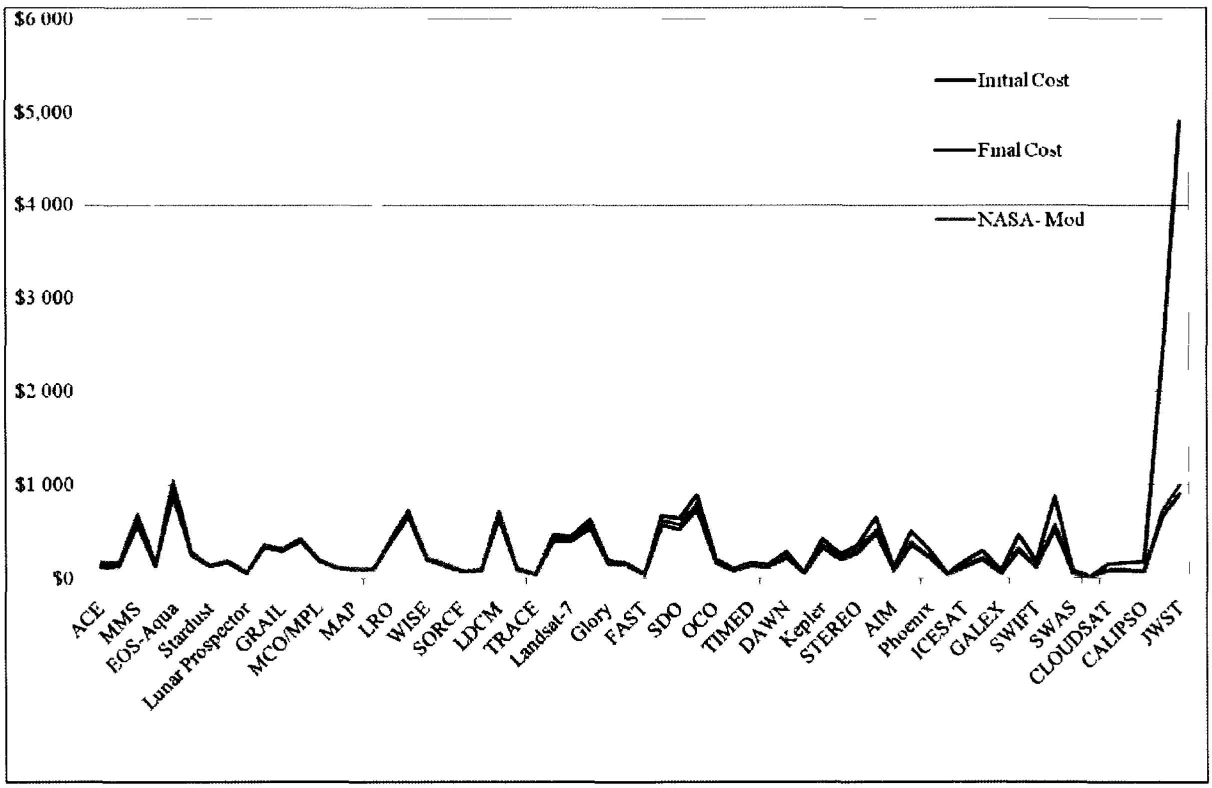

Figure 40. Applied Conservative NUC for Moderate Risk Level to NASA Data

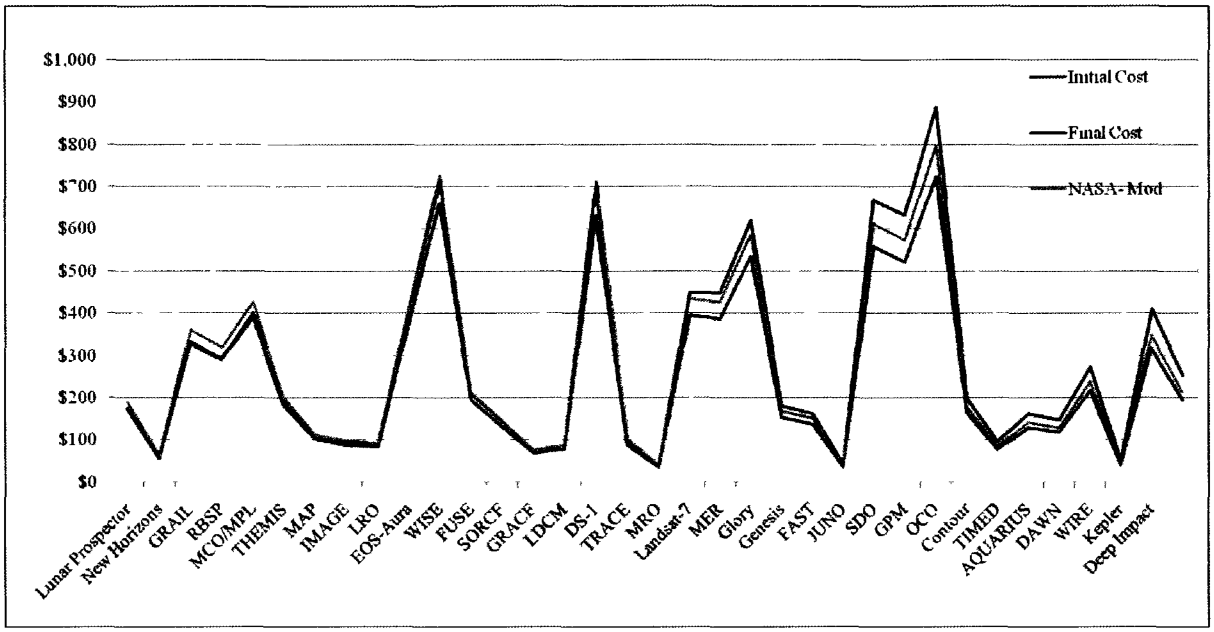

Figure 41. Applied Conservative NUC for Moderate Risk Level for NASA Data up to 30% of the Cost Growth

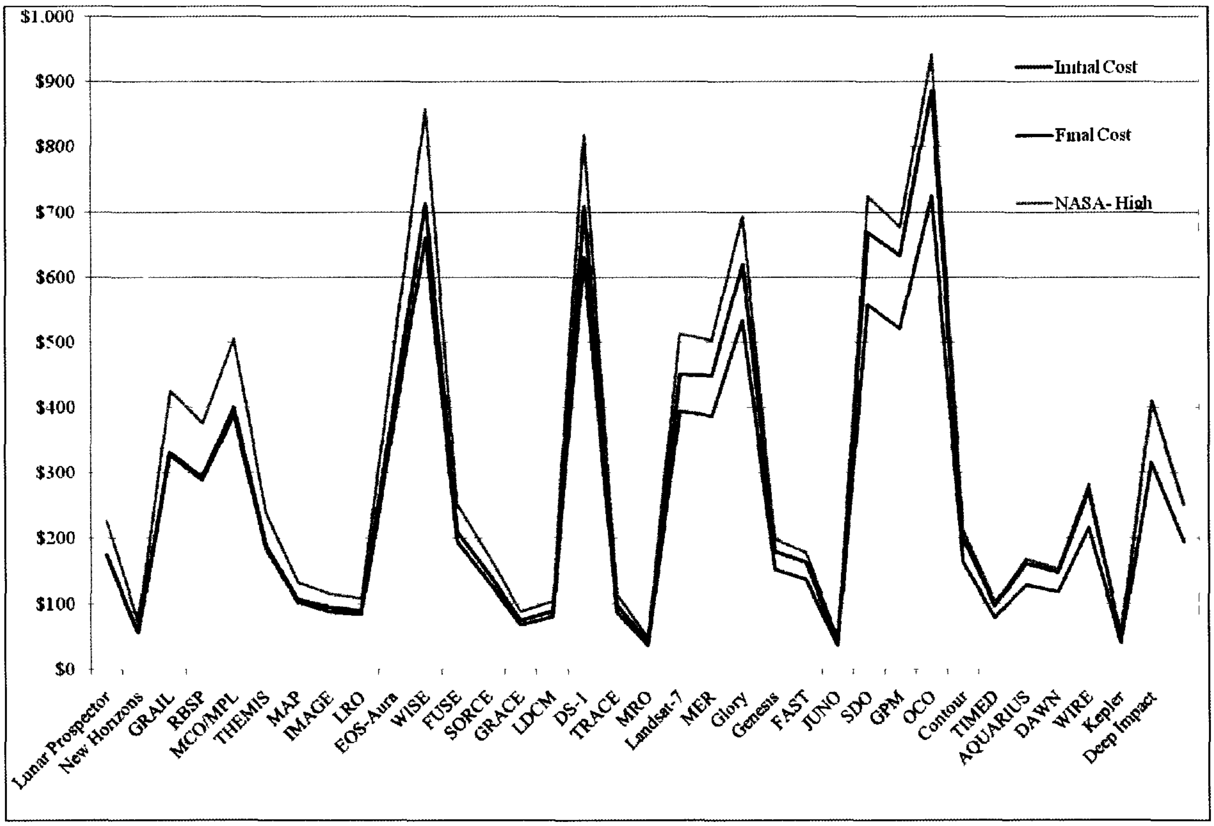

Figure 42. Applied Conservative NUC for High Risk Level to NASA Data

4.2.2 Aggressive Factors

1. All data on aggressive uncertainty factors with three risk levels and all missions (Figure 43).
2. Data on aggressive uncertainty factors with moderate risk level and all missions (Figure 44).
3. Data on aggressive uncertainty factors with moderate risk level and missions with less than 100% cost growth (Figure 45).

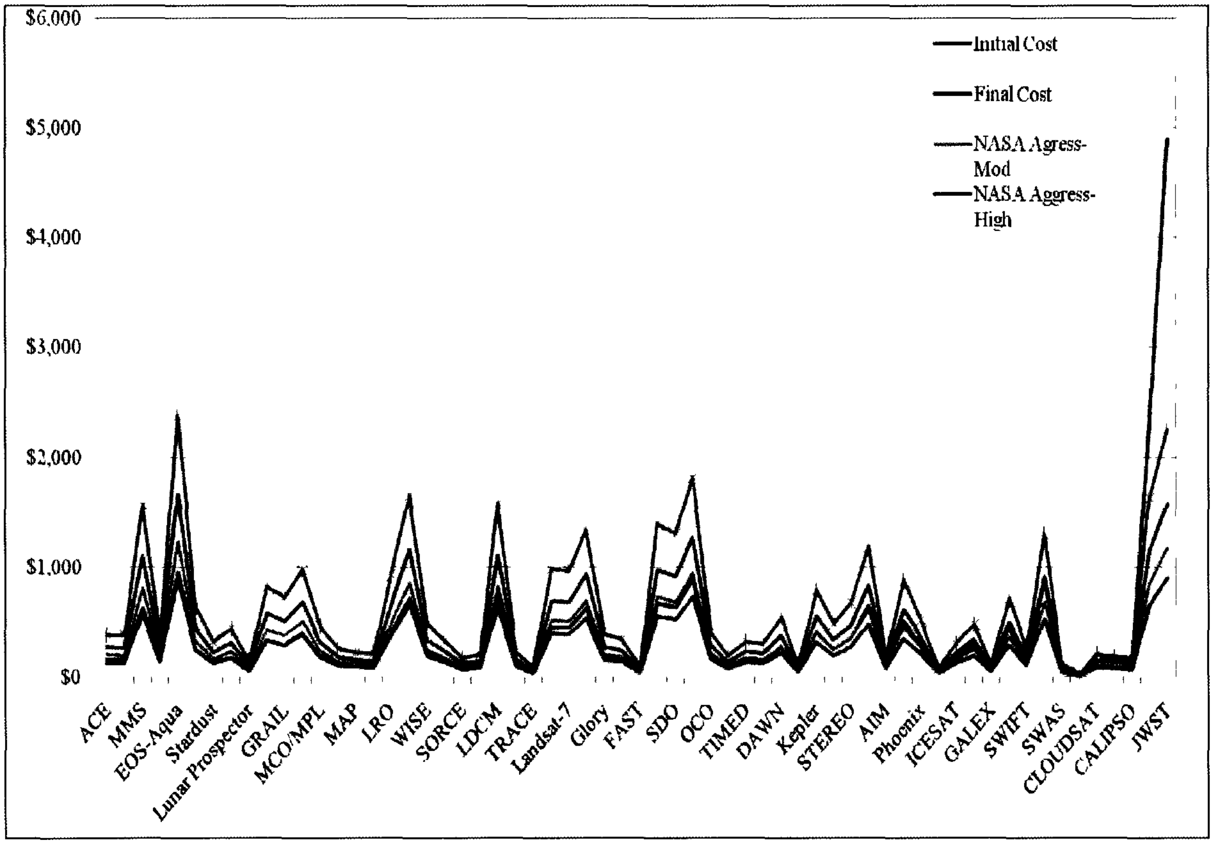

Figure 43. Applied Aggressive NUC for Three Risk Levels to NASA Data

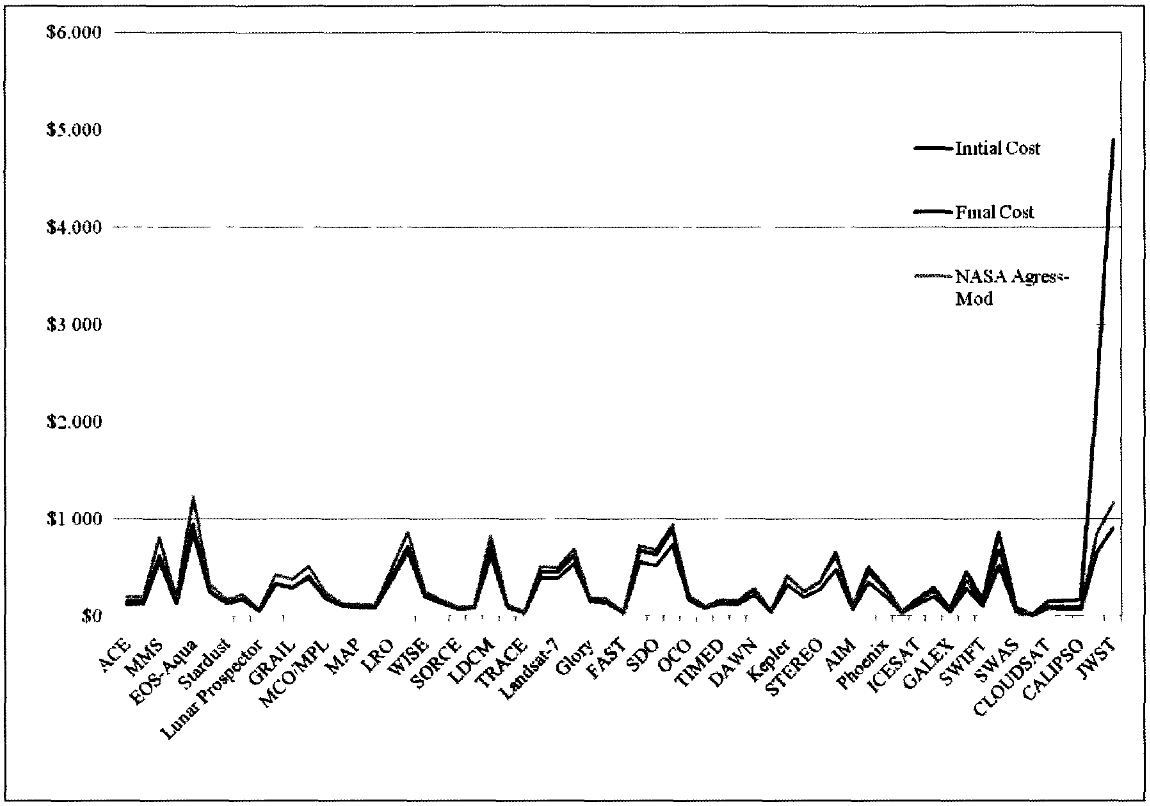

Figure 44. Applied Aggressive NUC for Moderate Risk Level to NASA Data

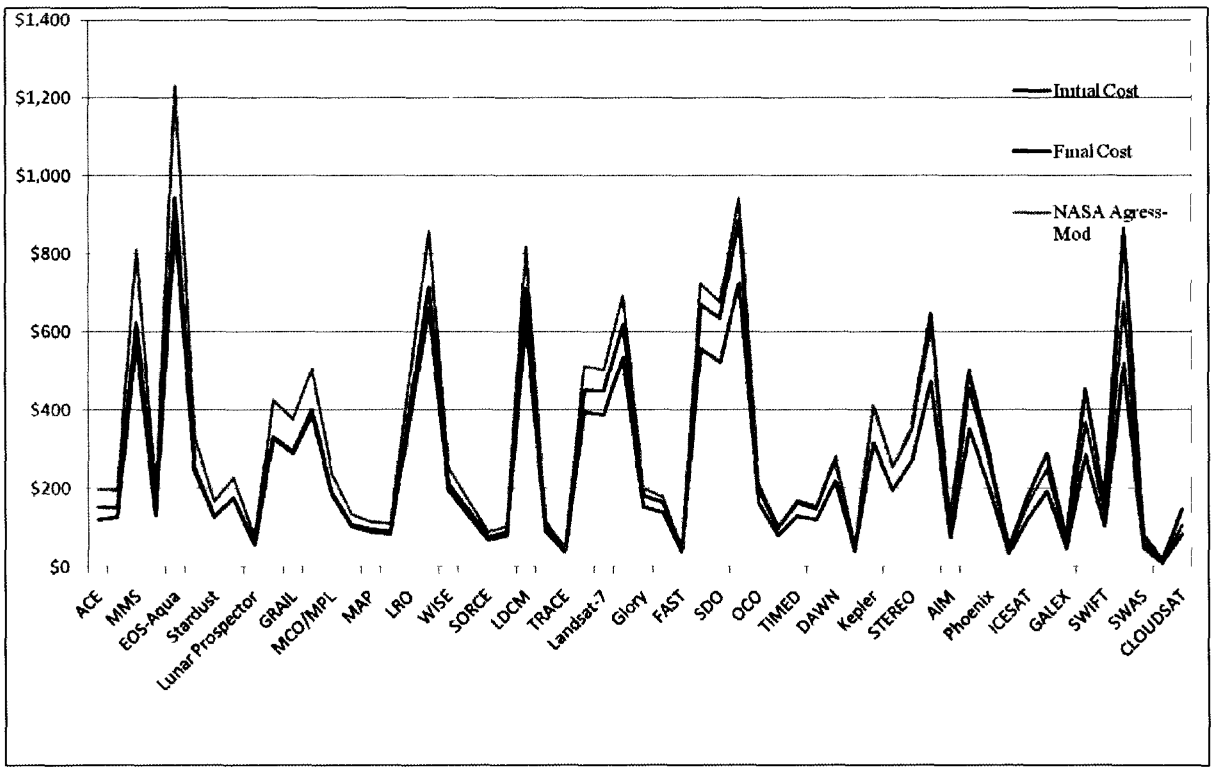

Figure 45. Applied Aggressive NUC for Moderate Risk Level for NASA Missions with Less than 100% Cost Growth

From the figures above, the aggressive factor for moderate risk level covers 80% of the data, thus factors will provide better predictions and estimates for NASA projects.

Finally, the data analysis should empirically validate previous cost estimates and their associated risk analyses. Such a validation would help to improve both data quality and risk estimation in NASA missions. It is vital to the credibility of both uncertainty factors and its applications in NASA missions. This qualitative method can be valuable for providing a better understanding of estimating overall risks for projects.

4.3 Landsat Data Continuity Mission (LDCM) Estimating Case

The LDCM is the successor mission to Landsat 7. Landsat satellites have continuously acquired multi-spectral images of the global land surface since the launch of the Landsat 1 in 1972. The Landsat data archive constitutes the longest record of the land surface as viewed from space. The LDCM objective is to extend the ability to detect and quantitatively characterize changes on the global land surface at a scale where natural and man-made causes of change can be detected and differentiated. It will continue to obtain valuable data and imagery to be used in agriculture, education, business, science, and government. The LDCM, consistent with U.S. law and government policy, will continue the acquisition, archiving, and distribution of moderate-resolution multispectral imagery affording global, synoptic, and repetitive coverage of the Earth's land surface at a scale where natural and human-induced changes can be detected, differentiated, characterized, and monitored overtime. The science focus area served by LDCM will include: carbon cycle, ecosystems, biogeochemistry, and Earth surface and interior. Plan Sub-goal 3A: Study Earth from space to advance scientific understanding and meet societal needs. NASA and Department of Interior (DOI) U.S. Geological Survey (USGS) were identified as the Landsat Program Management team under the authority of U.S. Code Title 15, Chapter 82, "Land Remote Sensing Policy" and Presidential Decision Directive NSTC-3, "Land Remote Sensing Strategy."

The lead NASA Center for LDCM is the Goddard Space Flight Center (GSFC). The lead USGS center for LDCM is the Center for Earth Resources Observation and Science (EROS). The LDCM observatory is anticipated to launch aboard an Atlas V Model 401 launch vehicle from Vandenberg Air Force Base (VAFB) no earlier than December 2012. USGS is responsible for the development of the Ground System, excluding procurement of the Mission Operations Element (MOE), Flight Operations Team (FOT), and establishment of the Mission Operations Center (MOC). The USGS is also responsible for LDCM mission operations, after completion of the on-orbit checkout period. NASA will serve as the system integrator for LDCM and lead the mission systems engineering effort. LDCM is being undertaken by NASA as a stand-alone ('free-flyer') mission planned for launch as soon as possible to provide continuity of Landsat data. Launch is scheduled in December 2012.

Several independent reviews have been conducted to ensure that the project is in compliance with technical, cost and schedule requirements. The LDCM has four main elements: Operational Land Imager (OLI), Thermal Infrared Sensor (TIRS), Spacecraft, and Ground Operation. Table 13 shows the independent review board qualitative scoring of the cost uncertainties for the four main elements.

Table 13. Qualitative Cost Uncertainty Rating for the LDCM

Risk Level	OLI	TIRS	Spacecraft	Ground Operations
Moderate	X			X
High			X	
High +		X		

This mission completed four independent reviews that assessed the status of the mission from the technical and programmatic viewpoint. Table 14 is focused on the initial cost for each review. It is evident that the cost growth from System Requirements Review/Mission Definition Review (SRR/MDR) to PDR from the project perspective is approximately 40%. From the PDR to CDR, the cost growth is 4%. At this point in the mission, there is a cost growth on 46% of the mission because of the addition of a 17-month schedule. This is a valid increase, as the initial schedule was so unrealistic. Additionally, all the TBDs have not yet occurred because the project is still under development.

Table 14. LDCM Life-Cycle Reviews Cost Changes

LDCM Milestones	**Initial Cost ($M)**	**Initial Cost ($M) IPAO**
SRR/MDR	$645	$888
PDR	$904	$1071
CDR	$941	$1016
SIR	TBD	TBD

The technical approach for LDCM refers to any potential technical risk that has a known impact associated with cost or schedule and technical uncertainty and growth. This includes such things as technology development or inadequate technical margins. If the NUFs are used for this project as an aggressive moderate risk with a factor of 1.3, one can predict the cost growths will be 30% from the PDR. Thus, total actual cost will be $1175M and will fall in the middle of the lognormal distribution (see Figure 46).

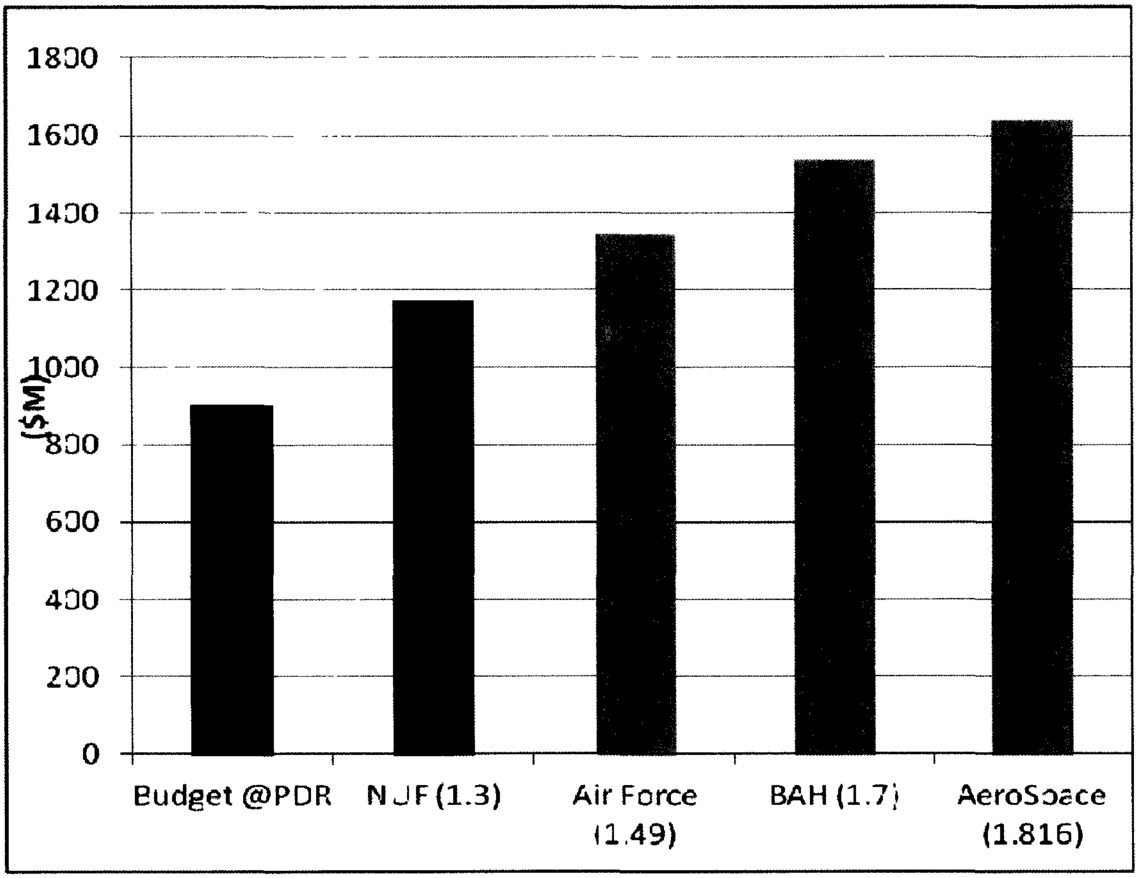

Figure 46. LDCM Predicted Cost Growth Four Uncertainty Factors

4.4 Final Comparison

The last verification point for the NUF is comparing the four methods of estimating the uncertainty factors with the actual NASA data set (Table 15). There are five completed missions that were not used to develop the NUF lognormal distribution for tested and used data sets (see Figure 9).

Table 15. Comparison of Cost Growth Using Different Uncertainty Factors- Test Case for NUF

			Risk Factor as Aggressive and Moderate Risk Level			
Mission	**I-Cost**	**F-Cost**	**NUF(1.3)**	**Aerospace(1.816)**	**Air Force(1.49)**	**BAH(1.7)**
TRACE	$35.6	$40.3	$46.28	$64.65	$53.04	$60.52
SDO	$520.8	$633.5	$ 677.04	$945.77	$775.99	$885.36
DAWN	$216.9	$272.9	$ 281.97	$393.89	$323.18	$368.73
PHOENIX	$207.0	$296.5	$ 269.10	$375.91	$ 308.43	$351.90
CLOUDSAT	$80.2	$144.0	$ 104.26	$145.64	$119.50	$136.34

Figure 47 shows that the NUF is very close to the final cost. Thus, NUF provides a better estimate than the others NUFs as displayed in the selected five missions. Note that for the Trace, Solar Dynamics Observatory (SDO), and Dawn missions, the NUF are within 2% of the final cost growth but, for the Phoenix and CloudSat missions, the final cost growth is higher than NUF because it is higher than normal NASA cost growth; however, the NUF is closer than other uncertainty factors. These two missions should have been classified as a high level of risk and semi-aggressive uncertainty; thus the NUF should been 1.5, which yields $310.5 for Phoenix and $120.3 for CloudSat.

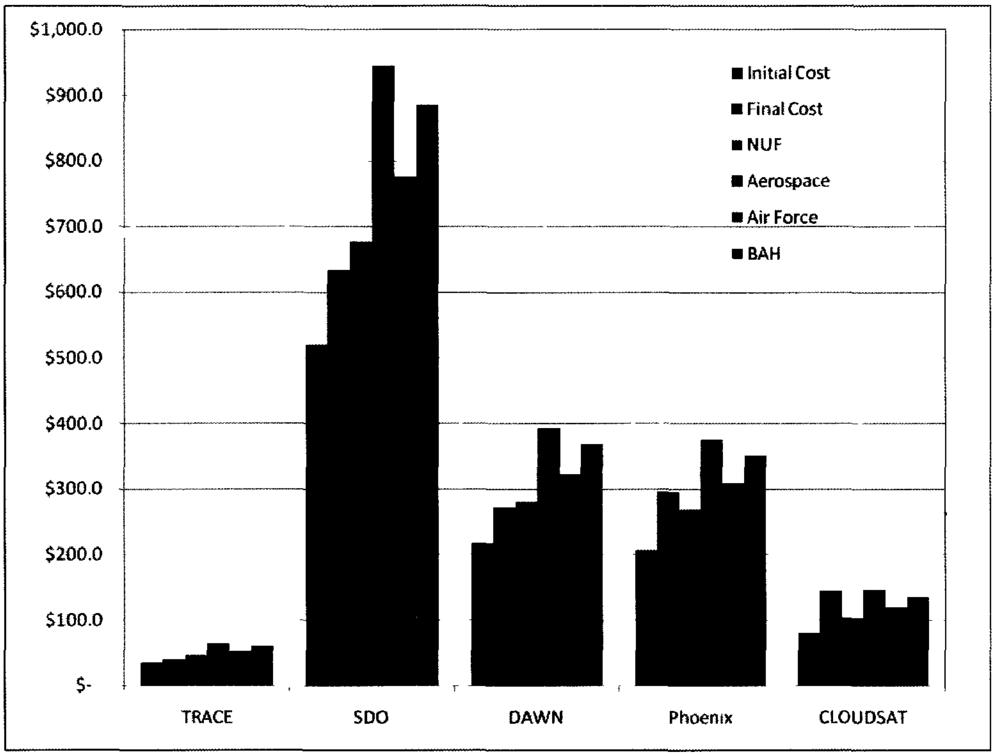

Figure 47. Estimate Cost Growth with Four Uncertainty Factors Methods

Finally, using the NUFs for development of initial cost estimating for new P/p, which should yield a more realistic estimate and help determine a final actual cost is recommended. Furthermore, the gathered data allows one to form an informed *a priori* assessment of future cost growth. Uncertainty in future cost growth is quantified by a probability distribution. Arguments based on theory and analyses suggest that the lognormal distribution is a reasonable choice. Finally, NUFs provide the parameters for the distribution that best fit the NASA cost growth experience.

CHAPTER 5

CONCLUSIONS

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Joseph B[illegible]dara[illegible]co [illegible]

NASA is a good investment of federal funds and strives to provide the best value to the nation. NASA has consistently budgeted to unrealistic cost estimates, whose unreality is reflected in the cost growth in many of its programs. NASA has been using available uncertainty factors from the Aerospace Corporation, Air Force, and BAH to develop projects risk posture. NASA has no insight into the development of these factors and, as demonstrated here, this can lead to unrealistic risks in many NASA P/p. This contribution of this project is the development of NASA missions' uncertainty factors from actual historical NASA projects in order to estimate cost for independent reviews that provide NASA senior management with the information and analysis to determine the appropriate decision regarding P/p at KDPs.

5.1 Summary of Contributions

This doctoral project has special contributions to cost estimation for NASA P/p and specifically for the independent analysis groups that are faced with the challenge of providing realistic cost estimates for use in Agency-level decision-making. The highlights of contributions are as follows:

5.1.1 Generated insights into NASA Cost Growth

This project investigated recent NASA cost growth history for sixty science missions. These missions included both Space and Earth Science. These insights are best summarized in Chapters 3 and 4. Reasons for cost growth are varied and often poorly understood. At the onset of a Program, technical details are also poorly understood. Program Managers provide detailed estimates that lack rigor. It is difficult to push-back without some sort of "report card" for the community. This research summarizes the reasons for cost growth in many science missions.

5.1.2 Developed NASA Uncertainty Factors (NUFs)

This project examined NASA historical cost growth data and developed NUFs to be implemented in realistic estimates of probability cost distributions. These NUFs are distinctly different from those currently being used in several ways. In Chapter 4, it is shown that the NUFs provide some guidelines for cost growth that would be useful in many ways. For example, briefing senior management on the magnitudes of cost growth typical of NASA projects could be accomplished with Table 12. Furthermore, these factors can be used by decision-makers to assess the difference between an independent estimate and a Program Manager's advocacy estimate which is worth reconciling. A difference of 10%, for example, might be judged to be insignificant given the amount of cost growth experienced in general on all Programs.

5.1.3 Identified Better-Fitting Cost Distributions for NASA

The purpose of this research was to develop a risk distribution for NUFs that would be applicable in the early stages of the cost estimation of NASA missions. It has been found that NASA cost growth fits a lognormal uncertainty distribution. Coupled with the NUFs, the cost risk analysis would produce a more accurate estimate of final costs. This is a significant contribution in light of current bias at NASA toward underestimating costs. Additionally, the probability distribution of cost growth for sixty NASA missions provides evidence of an exponentially-long tail. This is evidence that "Black Swan" programs are not exceptionally rare. It is a challenge to the programmatic and technical communities to spot these types of programs and then have to bring that bad news to the discussion table. It is recommended that for the programmatic analysts use Figure 34 to remind Program Managers that major problems in program execution are not simply a rare case of "bad luck." They happen more often than one would like to admit.

The cost risk analysis will be better understood because the uncertainty estimating will produce a more realistic estimate, in lieu of the signification bias toward underestimating that the Agency experiences. As discussed above, this project proved that the factors developed are feasible, more relevant to NASA's missions, and useful for estimating the cost risk of future missions.

5.2 Limitations of NASA Uncertainty Factors

As with any estimating method, there are limitations to this approach. The NUFs implementation has great dependency on the cost analysts for selecting the best range for the specific mission. Then, usage of the right factors contains a great deal of uncertainty with itself. Additionally, this method is an approximation approach, so some missions may fall outside these factors. Finally, expert judgment goes hand in hand with NUF usage. One must understand that these factors are based on historical data, which may not be relevant in the future due to new manufacturing processes, new technologies, and better productivity than the historical data supported.

5.3 Future Work

The following areas can be improved:

1. The results could be made statistically relevant by simply increasing the number of historical missions captured in the database. Any increase in the number of missions in the database would result in the increased accuracy of the results.
2. In addition to increasing the accuracy of the results, studying additional historical missions for cost growth and risk data could also be used to provide a good check for the methodology that was developed through this project. These results could then be checked against actual data for determining where the actual cost of the mission is contained within the predicted estimate.
3. Test the NUF for missions in various life-cycle phases and compare the results to this project to determine if change has any effect on the life-cycles phases on the NUF.
4. Emphasize whether the understanding of the technical and programmatic risk during the missions' reviews will provide more accurate prediction of future cost growth for those missions.
5. The Microsoft® Excel-based tool that was developed for this project is very preliminary and basic. A more user-friendly tool should be developed to enable the methodology to be used by individuals who are not familiar with the research task that developed it. This would greatly enhance the applicability of the factors.
6. The factors have to be accepted by the cost analysts' community for implementation by the Agency and consider developing an Agency standard to request the usage.

This research provides an important contribution to the discipline of cost estimating. In particular, it has developed a solid database of actual cost growth history and adds some statistical rigor to the derivation of cost growth factors based on this data. Additionally, it is expected that this work will be referenced for independent cost estimates, correction of advocacy-bias in project-generated estimates, and other programmatic work.

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Appendix A

Project Proposal Plan

The research project will use mixed-method design, but mostly it is a quantitative research approach that seeks prediction for generalization to other NASA projects. The qualitative portion will come toward implementation of the developed NUFs. The following proposed steps will be conducted to complete this project:

1. Literature review of NASA projects cost and schedule growth
2. Identification of NASA projects
3. Data selection and analysis
4. Expert opinion and relevant working testing and evaluation
5. Develop a method of analysis
6. Develop NASA uncertainty factors
7. Test factors
8. Compare results
9. Make recommendations to implement the developed process
10. Publish the work
11. Complete research project

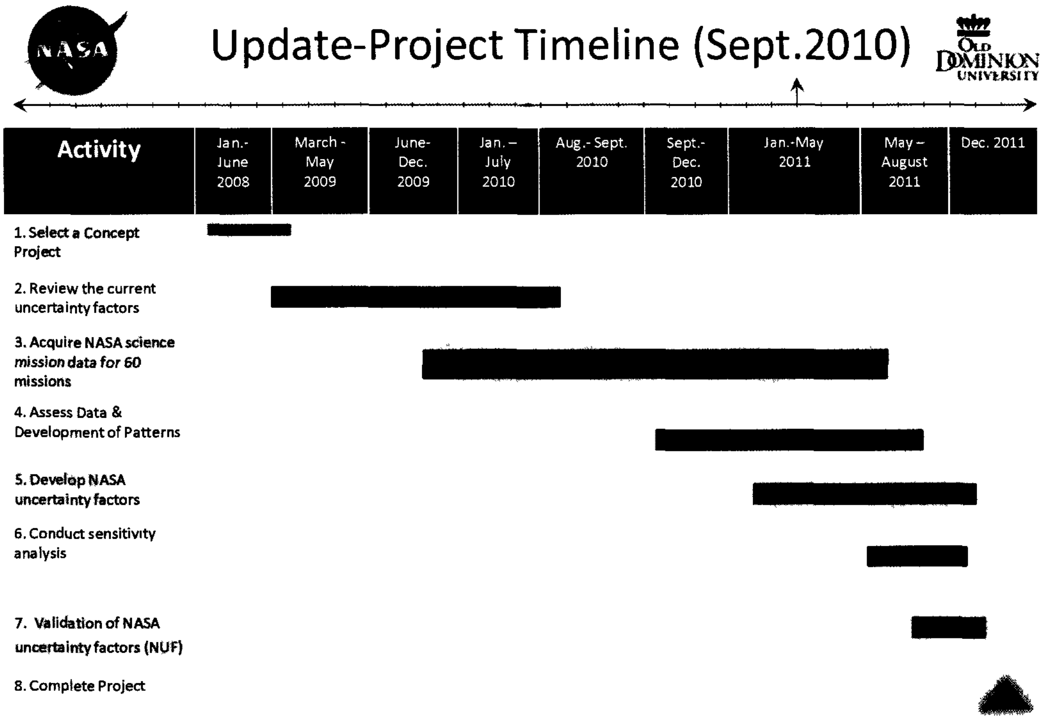


Figure 48. Research Project Timeline

Appendix B

NASA Cost Risk Policy

There is no specific cost risk policy that directs the cost estimator on how a cost risk assessment should be performed and included in a cost estimate. The only requirement is that a cost risk assessment has been conducted, the results incorporated into the estimate and the probabilistic cost estimate is presented at the 70% CL. NASA Policy Directives (NPDs) are policy statements that describe what NASA must do to achieve its vision, mission, and external mandates and who is responsible for carrying out those requirements. NASA Procedural Requirements (NPRs) provide Agency-mandatory instructions and requirements to implement NASA policy as delineated in an associated NPD. The following NPDs and NPRs provide information pertaining to NASA's cost risk requirements. These NPRs in conjunction with the Cost Risk volume of the NASA CEH provide the guidance and references for the NASA cost estimator to conduct the cost risk estimate as appropriate.

B.1 NPR 7120.5 Space Flight Program and Project Management Requirements

NPR 7120.5, NASA Space Flight Program and Project Management Requirements, (http://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal_ID=N_PR_7120_005D)covers requirements by which NASA formulates and implements space flight P/p, consistent with the governance model contained in NPD 1000.0,NASA Strategic Management and Governance Handbook, (http://nodis.hq.nasa.gov/displayDir.cfm?t=NPD&c=1000&s=0).

Specific to cost risk, this NPR covers P/p management's cost risk roles and responsibilities as well as P/p cost risk requirements by life-cycle phase. This includes:

- Risk assessments
- Risk evaluations
- Risk mitigations
- Identification of margin and reserves
- Associated oversight and approval processes

A number of cost risk related activities are required early in the project's life-cycle (Pre-Phase A through Phase B). Listed below are required activities or products relevant to cost risk during a program or project's life-cycle:

1. A high-level WBS consistent with the NASA standard space flight project WBS, schedule, and a rough order of magnitude cost estimate and cost range.
2. A baseline mission concept document that includes key risk drivers and mitigation options.
3. A preliminary full cost life-cycle cost estimate that includes reserves, along with the level of confidence estimate provided by the reserves based on a cost risk analysis.

The instructions and requirements stated in this NPR are associated with the policy set forth in NPD 7120.4C, NASA Program/Project Management (http://nodis3.gsfc.nasa.gov/ displayDir.cfm?t=NPD&c=7120&s=4C). This document describes the management system governing formulation, approval, implementation, and evaluation of P/p.

B.2 NPR 8000.4 Risk Management Procedural Requirements

NPR 8000.4, NASA Risk Management Procedural Requirements (http://nodis3.gsfc.nasa.gov/ displayDir.cfm?t=NPR&c=8000&s=4) outlines program and project requirements and information that pertain to risk management, as required by NPR 7120.5D and NPD 8700.1, NASA Policy for Safety and Mission Success (http://nodis.hq.nasa.gov/ displayDir.cfm?t=NPD&c=8700&s=1C). This NPR also introduces the continuous risk management (CRM) process and defines risk management concepts, risk management requirements, and risk management responsibilities.

CRM is a 6-step process that is used to manage risk and achieve planned objectives. This process involves identifying, analyzing, planning, tracking, controlling, documenting, and communicating risks effectively.

NPR 8000.4 requires P/p to perform risk analyses that consist of estimating the likelihood and the consequences of risks and the timeframe in which action must be taken on an identified risk to avoid harm. The recommended methods of analyzing risks include, but are not limited to, the following:

- Individual or group expert judgment.
- Statistical analysis of historical data.
- Uncertainty analysis of cost, performance, and schedule projections (consists of building and running a probabilistic model of the system under investigation, including the chance variation inherent in real-life cost, performance, and schedule).

B.3 Cost Risk Management Requirements in NPR 8000.4

NPR 8000.4 Chapter 4, "Special Requirements for Programs and Projects," paragraph 4.2 "Cost Risk Management," requires cost risk management to be part of the CRM process and delineates specific cost risk requirements, but does not describe the process or how they are to be implemented. This cost estimating handbook contains that information.

B.4 Cost-Risk Management

While some cost-risk methodologies can be generalized to Space Flight Programs, or even non-Space Flight endeavors, the focus and the tools discussed here are applied to Categories I & II major Space Flight Projects. The objective of cost risk management is to continuously determine the rolled-up risk impact on the cost of the P/p by organizing, obtaining, and using cost-risk information.

Stakeholder interest in integrated cost-risk was codified in June 2006 with the OMB update of Circular A-11, Part 7 and the Supplement to Part 7 (Capital Programming Guide) and in July 2006 with the update of the FAR (FAR Case 2004-019) that implements the earned value management system (EVMS) policy in accordance with the changes to Circular A-11, Part 7. These updates require the creation and management of risk adjusted budgets.

This supplemented GAO interest to better NASA cost-risk management as documented in the May 2004 GAO report on NASA cost estimating.

Cost risk management integrates the CRM process, cost estimating, cost-risk assessment/analysis (utilizing the identified risks in the project risk list and the cost estimate), and EVM, with procurement, source selection, cost data collection, and cost data analysis as supporting disciplines.

There are three activities that make up integrated cost-risk: Identify and Quantify Cost-Risk; Establish Cost-Risk Reporting; and, Manage Cost-Risk Using Reported Data. These activities are summarized below:

Identify and Quantify Cost-Risk

- Identify and assess risk.
- Translate risk assessment into cost impact.
- Perform "S"-curve and CRM scenario-based cost-risk.
- Incorporate CRM scenario-based and "S"-curve cost-risk in CADRe Part C life-cycle cost estimate (LCCE).

Establish Cost-Risk Reporting

- Develop RFP CADRe & EVM Data Requirements Description (DRD) and equivalent project plan requirements.
- Evaluate EVM and LCCE DRDs in proposals/project plans.
- Perform Integrated Baseline Review.

Manage Cost-Risk Using Reported Data

- Perform EVM performance measurement & CADRe "S"-curve analysis.
- Compile end-of-contract cost-risk data for database updates, data evaluation, and analysis and cost-risk algorithm updates.

Cost risk management is performed in three overlapping stages during project life-cycle phases. Generally speaking, identification, quantification and establishing cost-risk reporting occur at the end of each phase, followed by the use of that reporting for cost-risk management in the next phase. This cycle repeats as illustrated in Figure 49.

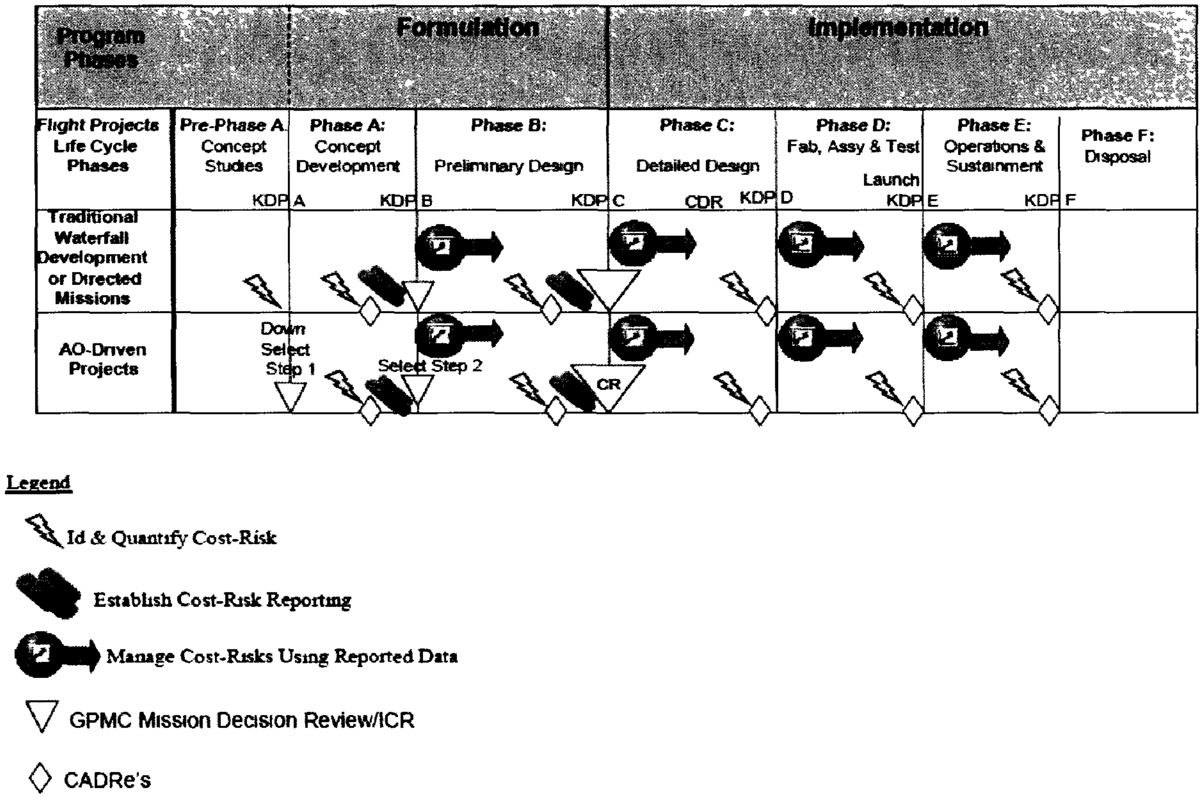


Figure 49. When Integrated Cost-Risk is Required

Pre-Phase A/Phase A to Phase B

In pre-Phase A and the early Phase A of formulation, P/p should identify and quantify cost-risk to be incorporated in the project's CADRe LCCE that forms the basis for the proposed project budget.

The CADRe has three-parts: Part A - narrative project description; Part B - technical characteristics; and, Part C - risk-adjusted LCCE. Part C requires any actual costs-to-date plus an estimate-to-complete with cost methodology and cost-risk quantification documentation. Near the end of Phase A, an ICE is performed assessing cost and cost risk in preparation for transition to Phase B. CRM risk identification is a key input into cost-risk quantification for the project's CADRe LCCE. CRM risk likelihood-based cost impacts are compared with the cost estimating cost-risk impacts and reconciled to produce the project's CADRe LCCE. Also, in late Phase A, the project develops data requirements to establish cost-risk reporting for cost-risk management using the reported cost-risk data beginning early and extending throughout Phase B.

Phase B to Phase C

In late Phase B, P/p updates their CADRe LCCE including identification and quantification of cost-risk and documents reasons for cost growth for the final risk-adjusted budget for approval at confirmation. Once approved, the P/p incorporates the risk handling budgets for cost-risk in the EVMS's performance measurement baseline (PMB) to be tracked and managed in Phase C of implementation. Establishing new cost-risk reporting in Phase B is only activated if there are any changes necessary in the reporting data used in managing Phase C cost-risk. Projects then incorporate and budget risk handling tasks in their EVMS. Projects also flow down the requirements for cost-risk in any contractor's EVMS in all appropriate procurements.

Phase C to Phases D & E

The identification, quantification, and updating cost-risk reporting (if necessary) of integrated cost-risk is again repeated prior to entry into implementation of Phases D & E to manage cost-risk using reported data in those phases. Working synergistically with integrated cost risk and the EVM is used to plan and budget for risk handling and reporting. P/p offices will also specifically evaluate the EVM cost-risk handling performance measurement on a monthly basis.

EVMS Control Accounts contain work packages where risk handling activities are planned, budgeted, and measured. P/p meeting EVMS requirement thresholds incorporate meaningful, measurable, and relevant risk handling activities in the EVMS. Risk handling activities are budgeted, scheduled and assessed as part of the project's EVM planning and performance assessment process. EVM data is used to track performance measurement progress of the risk handling activities, against the project's integrated baseline, that is, the PMB integrated with the integrated master schedule (IMS). The rationale for this is that all risk handling activities ultimately involve use of project resources (e.g., personnel, schedule, and budget). EVM allows the project to plan and assess performance based upon an integration of these resources.

Performance against the plan and EVM reporting can include WBS elements identified as risky during integrated cost-risk activities to ensure the Project Manager has performance measurement information on those WBS elements most likely to cause cost and schedule problems.

Each month's EAC from the EVMS can include a cost-risk exercise resulting in an EAC cost-risk S-curve for the effort. The cost-risk S-curve provides higher quality information to the Project Manager about how confident he or she should be about the project's EAC versus the contractor's Latest Revised Estimate (LRE) that includes cost impacts due to current levels of risk. Using EVM metrics (e.g., Cost Performance Index (CPI); Schedule Performance Index (SPI); Schedule/Cost Index (SCI); etc.) in combination with Microsoft® Excel and Monte Carlo simulation software, Control Account and Work Package activity cost-risks can be modeled and statistically summarized for the S-curve evaluation.

EVM cost-risk reporting requirements should be described in the solicitation's data requirements section such that contractors understand that risks identified in the cost estimate, by the source evaluation boards and independent risk identification teams are to be reported in the EVM contract performance reports (CPR). Such CPR data requirement language should read like the following as developed by the EVM Working Group and posted on the Cost Analysis Division website.

Contents

The CPR shall include data pertaining to all authorized contract work, including both priced and unpriced efforts that have been authorized at a not-to-exceed amount in accordance with the Contracting Officer's direction. The CPR shall separate direct and indirect costs and identify elements of cost for all direct reporting. The CPR shall include Formats 1 through 5, down to a WBS Level -4. A lower level of reporting may be required for elements that are classified as "special interest" technical, schedule, or cost risk areas.

Earned value performance measurement data for government and/or contractor-identified medium- and high-risk WBS items shall be reported on Format 1 of the monthly CPR until such time as both government project management and the contractor agree that they no longer represent high risks. This reporting shall be at a level where the risk resides in the WBS. For medium- and high-risk elements lower than Level 4, specific narrative variance analyses are not required unless classified as "special interest".

To ensure an integrated approach to risk management, the data provided by this CPR DID shall be in consonance with the WBS, Integrated Master Schedule (IMS), Risk Management Processes, Plans and Reports (where required), Probabilistic Risk

Assessment Processes and Reports (where required), the CADRe and the Monthly/Quarterly Contractor Financial Management Reports (533/Q). The Financial Management Reports shall include reconciliation between the 533Q and the CPR. This reconciliation may be included within the required CPR formats.

Format

CPR formats shall be completed according to the instructions outlined in DI-MGMT-81466A and the following forms: Format 1 (DD Form 2734/1); Format 2 (DD Form 2734/2); Format 3 (DD Form 2734/3); Format 4 (DD Form 2734/4); and Format 5 (DD Form 2734/5). Samples of the forms are located at http://www.dtic.mil/whs/directives/infomgt/forms/ddforms2500-2999.htm. Variance analysis thresholds which, if exceeded, require problem analysis, narrative explanations and corrective action plan descriptions for all level three and other special interest WBS elements. Variance analysis thresholds will initially be +/- 10% of both current and cumulative cost and schedule variance to date. The variance analysis thresholds may change once the personnel evaluate the contractor's schedule and cost performance and risk.

Special emphasis should be placed in the variance analysis on cost and schedule growth linked to technical risks (e.g., technology development efforts, design engineering, integration, complexity, project management, systems engineering, duration constraints, etc.) identified by both the government and contractor.

Contractor format may be substituted for CPR formats whenever they contain all the required data elements at the specified reporting levels in a form suitable for NASA management use. The CPR shall be submitted electronically and followed up with a signed paper copy. The American National Standards Institute (ANSI) X12/XML standards (transaction sets 839 for cost and 806 for schedule), or the United National Electronic Data Interchange for Administration, Commerce and Transport (EDIFACT), http://www.unece.org/trade/untdid/welcome.htm equivalent, or any other electronic delivery method deemed acceptable by the Project Office shall be used for Electronic Data Interchange.

Refer to the EVM website, http://evm.nasa.gov, for additional information regarding EVM. Refer to NPR 7120.5 for EVM applicability and NASA requirements.

Appendix C

NASA Cost Risk as Part of the Cost Estimating Process

Cost risks are those risks due to economic factors such as rate uncertainties, cost estimating errors, and statistical uncertainty inherent in the estimate. Cost risk is dependent upon other fundamental risk dimensions (technical, schedule, and programmatic risks) so these must all be assessed to arrive at a true picture of project risk.

Cost-risk assessment takes into account cost, schedule, and technical risks that are then factored back into the cost estimate. To quantify the cost impacts due to risk, sources of risk need to be identified. NASA cost analysts should be concerned with three sources of risk and ensure that the model calculating the cost accounts for:

- **Risk inherent in the cost estimating methodology**. For example, if a regression-based cost estimating relationship (CER) is used, it has an associated standard error of the estimate (SEE), confidence intervals, and prediction intervals, any of which can be used to include cost estimating methodology risk in the estimate.
- **Risk inherent in the technical aspects of the systems being developed**. Into this category of risk fall risk sources such as the technology's state-of-the-art design/engineering (Technology Readiness Levels (TRLs)) are good indicators of this risk source), integration, manufacturing, schedule, complexity, etc. Quantifying the cost impacts due to these kinds of risk is not as statistically derivative as is CER risk. Figure 50 graphically displays the effects of cost estimating methodology risk and technical input risk.

- **Risk inherent in the correlation between WBS elements.** Correlation assessment determines to what degree one WBS element's change in cost is related to another's and in which direction. For example, if the cost of the satellite's payload goes up and the cost of the propulsion system goes up then there is a positive correlation between both subsystems' costs. Many WBS elements within space systems have positive correlations with each other and the cumulative effect of this positive correlation tends to increase the range of the possible costs.

Even as early as Pre-Phase A, it is important to capture risk in cost estimates, especially technical, schedule, programmatic and cost data. Even at this early stage, there are many risks that can and should be identified and addressed in a cost risk assessment. Cost estimating uncertainty, technical input variable uncertainty, and correlation risks all need to be considered. Schedule risk can be handled outside these three types of risk by applying probabilistic activity duration risk to the critical path analysis (CPA).

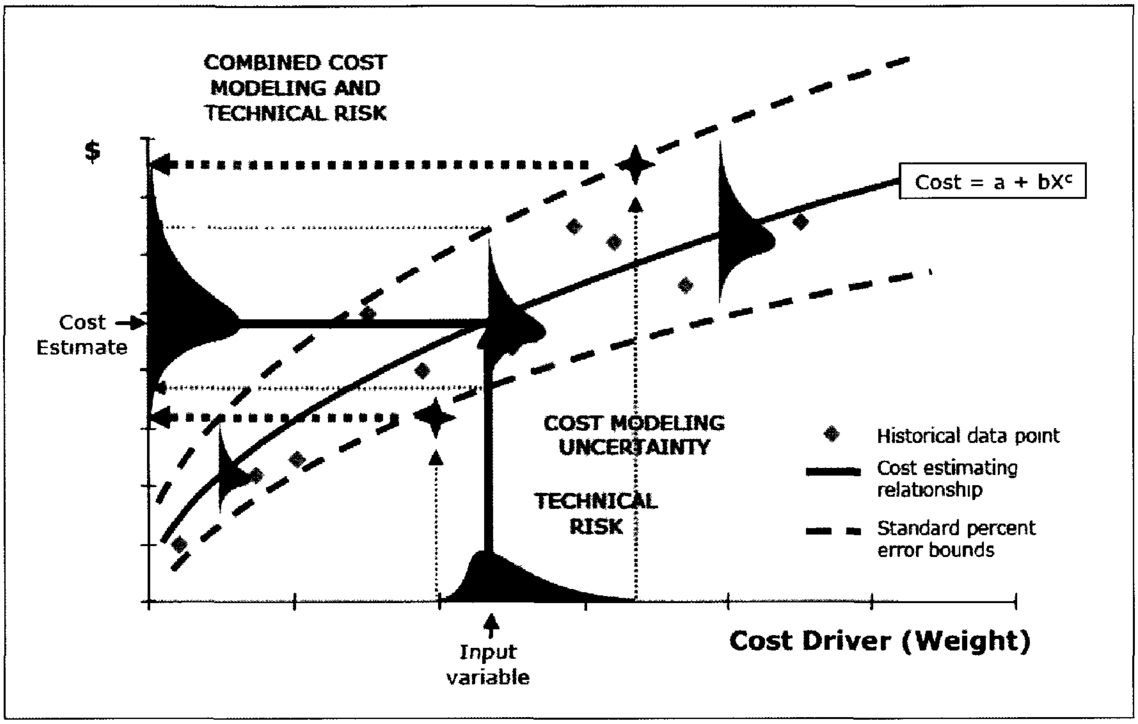


Figure 50. Cost Modeling and Technical Input Risk

Working with project office staff, the cost estimator should identify cost-risk drivers and vary the operating scenarios and input parameters through the conduct of comprehensive probabilistic and deterministic cost-risk and sensitivity analyses. It is the job of the cost estimator to estimate the effects of identifying, assessing, and analyzing cost-risk drivers (e.g., probabilistic cost-risk analysis) and varying cost drivers (e.g., deterministic cost-risk) and to revise the LCC estimates reflecting the selected variations, pointing out the relationship between the LCC and the key technical and/or operational parameter risks. Discrete technical cost-risk assessments involve identifying and cost estimating specific cost-driving technical risks.

For example, a notional new electronic component for a spacecraft might have risk in key engineering performance parameters (KEPPs) such as dynamic load resistance, operating voltage, power regulation, radiation resistance, emissivity, component mass, operating temperature range and operating efficiency. Technical staff can identify these KEPP risks during cost-risk assessment. Instead of probabilistic distributions and Monte Carlo simulations, however, mitigation costs for these risks are estimated based on their probabilities of manifesting discrete changes in the technical parameters (e.g., increased component mass or power regulation). Justifying the amount of cost risk dollars is a function of the detail specification of cost estimating, technical, and correlation risks that drive the cost risk range. Cost risk dollars that add, for example, 30% additional costs to the point estimate, have to be defensible with a cost-risk methodology that justifies the endpoints of individual WBS element cost-risk distributions, SEE regression line, and solid correlation coefficients.

As a project moves through the conceptual design phase, the range of feasible alternatives decrease and the definition of those alternatives increase. At this stage, there is a crucial need to identify pertinent cost issues and to correct them before corrective costs become prohibitive. Issues and cost drivers must be identified to build successful options. By accomplishing a cost estimate on proposed project alternatives, a Project Office can determine the cost impact of the alternatives. These cost drivers feed an increasingly detailed cost-risk assessment that takes into account cost, technical, and schedule risks for the estimate. The point estimate and the risk assessment work together to create the total LCC estimate.

As a project moves through the preliminary design phase and the project definition increases, cost estimators should keep the estimate up-to-date with definition changes and have a full cost risk assessment to defend the estimate, reduce updated estimate turn-around time, and give the decision-maker a clearer picture for "what if" drills or major decisions. The role of the cost estimator during this phase is critical. It is important to understand the basis of the estimate, from the technical baseline to the cost risk assessment and to be able to document and present the results of these efforts to the decision-makers. It is the cost estimator's responsibility to ensure the best possible LCCE with recommended levels of unallocated future expense (UFE) based on updated cost risk assessments in Phase B. These estimates will support budget formulation and source selection support in the transition from Phase B to Phases C/D.

When conducting Phase C/D estimates, new information collected from contractor sources and from testing must be fed back into the point estimate and the risk assessment, creating a more detailed project estimate. During this phase, the cost-risk assessment should be very detailed, not only including any changes in requirements or project design, but other details provided by project technical experts such as testing and schedule impacts. While the product is being designed, developed, and tested, there are changes which can impact the estimate and the risk assessment. It is critical to capture these changes to maintain a realistic program estimate now and in the future. During this phase, programmatic data may have just as much of an impact on the estimate and risk assessment as technical data.

Appendix D

The Twelve Tenets of NASA Cost-Risk

Tenet 1: NASA cost- risk assessment, a subset of cost estimating, supports cost management for optimum project management.

Tenet 2: NASA cost-risk assessment is based on a common set of risk and uncertainty definitions.

Tenet 3: NASA cost- risk assessment is a joint activity between subject matter experts and cost analysis.

Tenet 4: NASA cost-risk is composed of CERs and technical risk assessment plus cost element correlation assessment influenced by other programmatic risk factors.

Tenet 5: NASA technical cost-risk assessment combines both probabilistic and discrete technical risk assessments.

Tenet 6: NASA cost-risk probability distribution is justifiable and correlation levels are based on actual cost history to the maximum extent possible.

Tenet 7: NASA cost-risk assessment ensures cost estimates are likely-to-be-vice as specified for optimum.

Tenet 8: NASA cost-risk assessments account for all known variance sources and include provisions for uncertainty.

Tenet 9: NASA cost-risk can be an input to every cost estimate's cost readiness level (CRL).

Tenet 10: NASA cost-risk integrates the quantification of cost-risk and schedule risk by enlisting the support of NASA schedule and EVM analysts.

Tenet 11: NASA decision-makers need to know how much money is in the estimate to cover risk events, which WBS elements are allocated, and the CL of the estimate.

Tenet 12: NASA project cost-risk data, collected as a function of government and contractor project estimates and actual, contract negotiation and contract DRDs, is compiled into the OCE database.

Appendix E

Relationship of the Research Project and Published Literature

This section identifies key publications related to cost and schedule growth and offers an assessment of this literature in relation to the research project.

Research Problem Statement:

The research proposes to develop uncertainty factors from actual NASA historical project data to be used to classify risk for future cost estimation and support the independent reviews which inform NASA senior management and enable them to make the right decision regarding the project progress.

Problem Area 1 Determine NASA projects from which to gather data from as it relates to cost and schedule growth for science missions.
Problem Area 2 Develop a method to evaluate NASA project cost and schedule data by evaluating causes for growth and create measurement formalisms that account for multiple sources of growths.
Problem Area 3 Develop NASA Uncertainty Factors by capturing the trend of growth data from the selected science missions and compare these factors with other uncertainty factors.
Problem Area 4 Bring together research and uncertainty factors developed in problem area one through three into a coherent tool to be use in quantification risk for NASA future projects.

Table 16 presents an assessment of the literature with respect to these 4 problem areas. A color-coding scheme was defined and presented below. The color code indicates the degree to which the problem area is addressed in the referenced work.

COLOR CODING SCHEME
Red: Problem area not addressed in the referenced article or work.
Yellow: Problem area addressed to some extent in the referenced article or work; but, insufficient to meet this dissertation's research objectives.
Green: Problem area addressed in the referenced article or work.

Table 16. Literature Assessment Using the Four Problem Areas

Literature Assessment	Problem Area 1	Problem Area 2	Problem Area 3	Problem Area 4
Arena, V.A, and et al. (2006). "Impossible certainty: cost risk analysis for Air Force systems." Published 2006. by the RAND Corporation.	■	■	■	
Bitten, R.E., Bearden, D. A., Lao, L. Y., Park, T.H. (2003). "The Effect of Schedule constraints on the Success of Planetary Missions." 2003 Elservier Ltd.	■	■	■	
Bitten, R.E., Emmons, D.L, and Freaner, C.W. (2008). "In Search of the Optimal Funding Profile: the Effect of Funding Profiles on Cost and Schedule Growth." ISPA/SCEA 2008 Joint International Conference. The Netherlands May2008.	■	■	■	■
Bitten, R.E., Emmons, D.L., and Freaner, C.W. (2005). "Using Historical NASA Cost and Schedule Growth to set Future Program and Project Reserve Guidelines."	■	■	■	
Connley, Warren. (2004). *"Integrated Risk Management within NASA Programs/Projects,"* GSFC.	■	■	■	■
Coonce, T. (2008). *"NASA Cost and Risk Workshop,"* September 2008.	■	■	■	■
Cooper, L. (2003). *"Assessing Risk from a Stakeholder Perspective,"* IEEE, Paper# 1078.	■	■		■
Datta, S., and Mukherjee, S. (2001). *"Developing Risk Management Matrix for Effective Project Planning –An Empirical Study,"* by the Project Management Institution, Vol. 32, No. 2, pp 45-57.	■	■	■	■
Dillon, Robin. (2003). "*Programmatic Risk Analysis for Critical Engineering Systems under Tight Resource Constraints*," Operations Research, INFORMS, vol. 51, No. 3, May-June 2003, pp. 354 - 370.	■	■		■
Emmons, D.L., Bitten, R.E., and Freaner, C.W. (2006). "Using Historical NASA Cost and Schedule Growth to Set Future Program and Project Reserve Guidelines." IEEE Paper #1545. December.	■	■		■

Literature Assessment	Problem Area 1	Problem Area 2	Problem Area 3	Problem Area 4
GAO: Government Accountability Office, (2001). *"Major Management Challenges and Program Risks for NASA,"* report issued January 2001.	■	■		■
Grey, S. (1995). Practical Risk Assessment for Project Management. By John Wiley & Sons. Hulett, D. (2007). *"Integrated Cost/Schedule Risk Analysis,"* Program Management Challenge, 2007.			■	■
Hulett, D. (2007). *"Integrated Cost/Schedule Risk Analysis,"* Program Management Challenge, 2007.			■	■
Jiang, P., Haimes, Y. Y., (2004). "Risk Management for Leontief-Based Interdependent Systems," Risk Analysis, Vol. 24, No. 5.			■	■
Kaplan, S., 1997. "The Words of Risk Analysis," Risk Analysis, Vol. 4, No. 17.	■			■
Kellogg, R., Phan, S. (2002). " An Analogy-Based Method for Estimating the Costs of Space-Based Instruments," IEEEAC Paper #1160.	■	■	■	
Mlynczak, B., Perry, B., Science Support Office, NASA. "SMD Earth and Space Mission Cost Driver Comparison Study." March 2009.			■	■
Nadler, David. (2004). *"Building Better Boards,"* Harvard Business Review.			■	■
NASA Independent Program Assessment Office–Standard Operating Procedure, 2008.			■	■
NASA- NPR 7120.5 Space Flight Program and Project Management Requirement, March 6, 2007.		■	■	■
NASA-NPR 8000.4, issued on April 2002.	■	■	■	■
National Research Council. 2010. Controlling Cost Growth of NASA Earth and Space Science Missions. National Academy Press, Washington, D.C.			■	■

Literature Assessment	Problem Area 1	Problem Area 2	Problem Area 3	Problem Area 4
NASA 2008. "SMD Cost/Schedule Performance Study– Summary Overview." Presentation by B. Perry and C. Bruno, NASA Science Support Office; M. Jacobs, M. Doyle, S. Hayes, M. Stancati, W. Richie, and J. Rogers. Science Applications International Corporation. January 2008.			■	■
Parsons, V.S. (2007). *Searching for "Unknown Unknowns."* Engineering Management Journal, Vol. 19, No.1.		■	■	■
Pinto, C. A., Arora, A., Hall, D., Ramsey, D., Telang, R., 2004. "Measuring the Risk-Based Value of IT Security Solutions", *IEEE IT Professional*, v.6 no.6, pp. 35-42.	■			■
Pinto, C. A., Arora, A., Hall. D., Schmitz, E., 2006. "Challenges to Sustainable Risk Management: Case Example in Information Network Security," *Engineering Management.*	■			■
Rowe, W. D. (1994). "*Understanding Uncertainty,"* Risk	■		■	■
Ruckelshaus, William D., "Risk, Science, and Democracy," *Issues in Science and Technology*, Vol. 1, No. 3, 1985, pp. 19–38.	■		■	■
Schuyler, J. (2001). *Risk and Decision Analysis in Projects*, Library of Congress Cataloging in publication data.			■	■
Smart, C. (2007). *"Cost and Schedule Interrelationships,"* NASA Cost Analysis Symposium, Vol. 14, No. 5.			■	■

Appendix F

Non-NASA Uncertainty Factors

There are three different sets of uncertainty factors, below:

1. Uncertainty factors that were developed by Booz-Allen and Hampton from NRO missions.

Table 17. NRO Missions Uncertainty Factors

Level	Aggressive	Most Likely	Conservative
[redacted]			

2. Uncertainty factors that were developed from Air Force missions.

Table 18. Air Force Missions Uncertainty Factors

[redacted]			
Low	**0.95**	**1**	**1.1**
Low Plus	**0.96**	**1**	**1.23**
Moderate	**0.97**	**1**	**1.36**
Moderate Plus	**0.98**	**1**	**1.49**
High	**0.98**	**1**	**1.61**
High Plus	**0.99**	**1**	**1.74**
Very High	**1**	**1**	**1.87**
Very High Plus	**1**	**1**	**2**

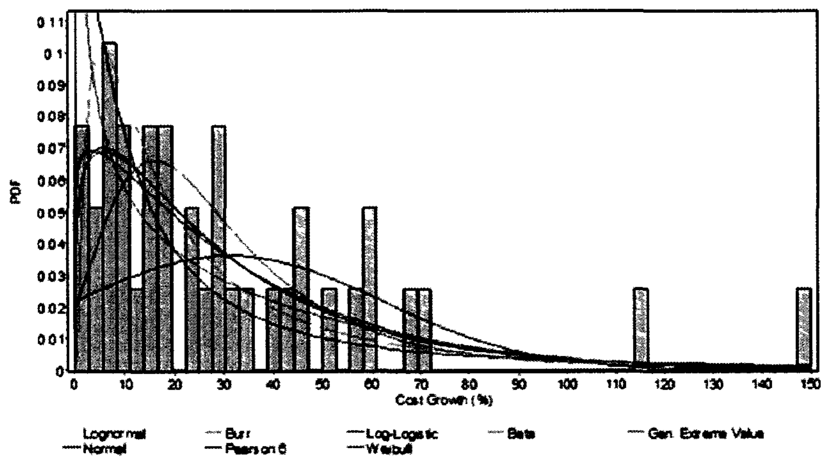
3. Uncertainty factors that were developed by Aerospace Corporation.

Table 19. The Aerospace Corporation Uncertainty Factors

Low	**0.977**	**1**	**1.117**	**0.05**
Medium Low	**0.932**	**1**	**1.35**	**0.15**
Medium	**0.887**	**1**	**1.583**	**0.25**
Medium High	**0.842**	**1**	**1.816**	**0.35**
High	**0.797**	**1**	**2.05**	**0.45**
High+	**0.752**	**1**	**2.5**	
Very High	**0.707**	**1**	**3**	
Very High +	**0.662**	**1**	**4.5**	
Extra High	**0.617**	**1**	**6**	

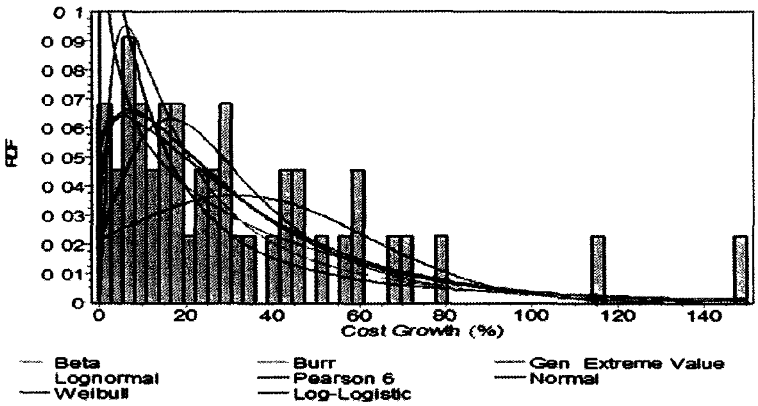
Appendix G

Goodness of Fit Summary for All Tested Cases



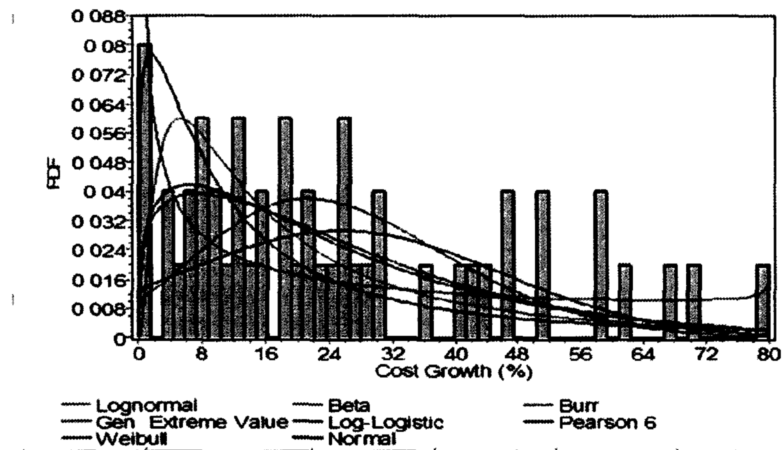
39 Missions - Goodness of Fit					
		Kolmogorov Smirnov		Anderson Darling	
#	Distribution	Statistic	Rank	Statistic	Rank
1	Beta	0 171151	8	4 05819	7
2	Burr	0 060433	1	2 09441	5
3	Gen Extreme Value	0 116518	5	0 414936	1
4	Log-Logistic	0 168776	6	4 93337	8
5	Lognormal	0 0952	2	3 37255	4
6	Normal	0 169327	7	1 26063	2
7	Pearson 6	0 060625	4	2 10491	2
8	Weibull	0 065478	3	2.03035	3

Figure 51. PDF and the Goodness of Fit of 39 Missions



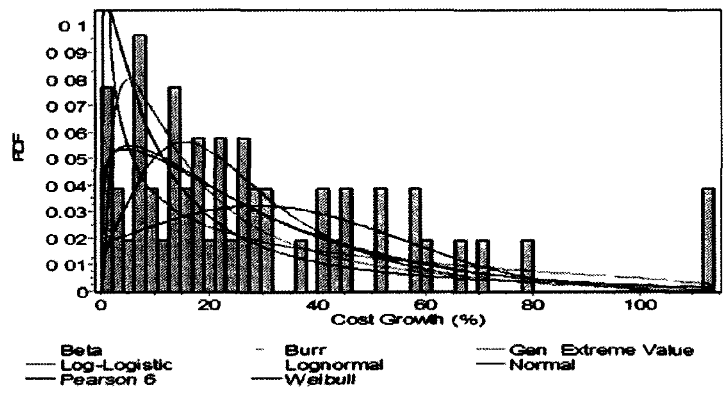
		44- Missions Goodness of Fit			
		Kolmogorov Smirnov		Anderson Darling	
#	Distribution	Statistic	Rank	Statistic	Rank
1	Beta	0 156002	6	3 36439	7
2	Burr	0 054062	1	1 97116	4
3	Gen Extreme Value	0 087518	5	0 313781	1
4	Log Logistic	0 165829	7	4 3697	8
5	Lognormal	0 093041	3	2 99895	2
6	Normal	0 170237	8	1 24002	6
7	Pearson 6	0 055114	2	1 97872	5
8	Weibull	0 066464	4	1 91762	3

Figure 52. PDF and the Goodness of Fit of 44 Missions



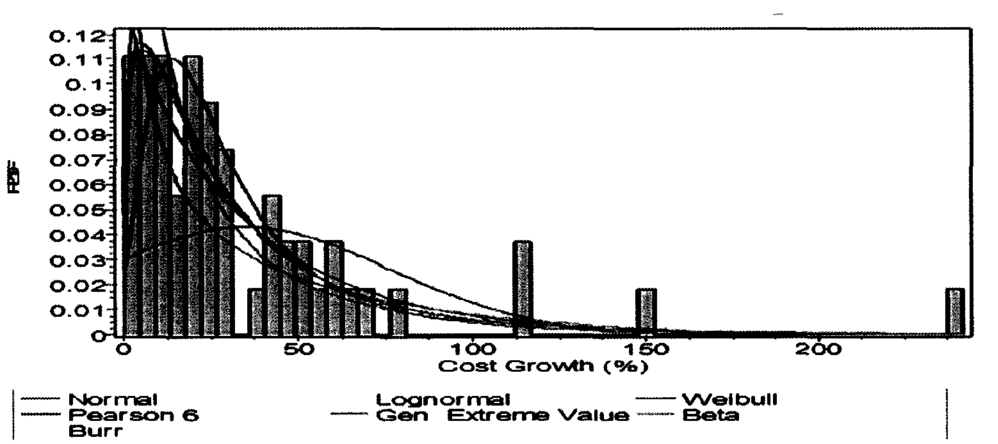
		50 - Goodness of Fit - Summary			
		Kolmogorov Smirnov		Anderson Darling	
#	Distribution	Statistic	Rank	Statistic	Rank
1	Beta	0 180336	7	5 67362	8
2	Burr	0 064221	2	2 44071	4
3	Gen Extreme Value	0 138442	6	1 63395	2
4	Log-Logistic	0 194152	8	5 47115	7
5	Lognormal	0 116387	3	3 85977	2
6	Normal	0 132523	5	0 924086	1
7	Pearson 6	0 06462	4	2 53775	5
8	Weibull	0 064221	1	2 44081	6

Figure 53. PDF and the Goodness of Fit of 50 Missions



		52 - Goodness of Fit - Summary			
		Kolmogorov Smirnov		Anderson Darling	
#	Distribution	Statistic	Rank	Statistic	Rank
1	Beta	0 196676	8	6 22535	8
2	Burr	0 059625	3	2 09265	3
3	Gen Extreme Value	0 107552	5	0 592606	6
4	Log-Logistic	0 178894	7	4 92971	7
5	Lognormal	0 10429	4	3 43451	1
6	Normal	0 162123	6	0 811959	2
7	Pearson 6	0 058975	1	2 15505	5
8	Weibull	0 059623	2	2 09266	4

Figure 54. PDF and the Goodness of Fit of 52 Missions



		54 Goodness of Fit - Summary			
		Kolmogorov Smirnov		Anderson Darling	
#	Distribution	Statistic	Rank	Statistic	Rank
1	Beta	0 211844	7	4 86752	7
2	Burr	0 057185	1	2 20558	6
3	Gen Extreme Value	0 104813	5	0 436167	1
4	Lognormal	0 091459	2	3 15553	3
5	Normal	0 2069	6	2 40286	5
6	Pearson 6	0 057745	4	2 21944	4
7	Weibull	0 082168	3	2 12592	2

Figure 55. PDF and the Goodness of Fit of 54 Missions

Appendix H

NASA Lognormal Distribution Model

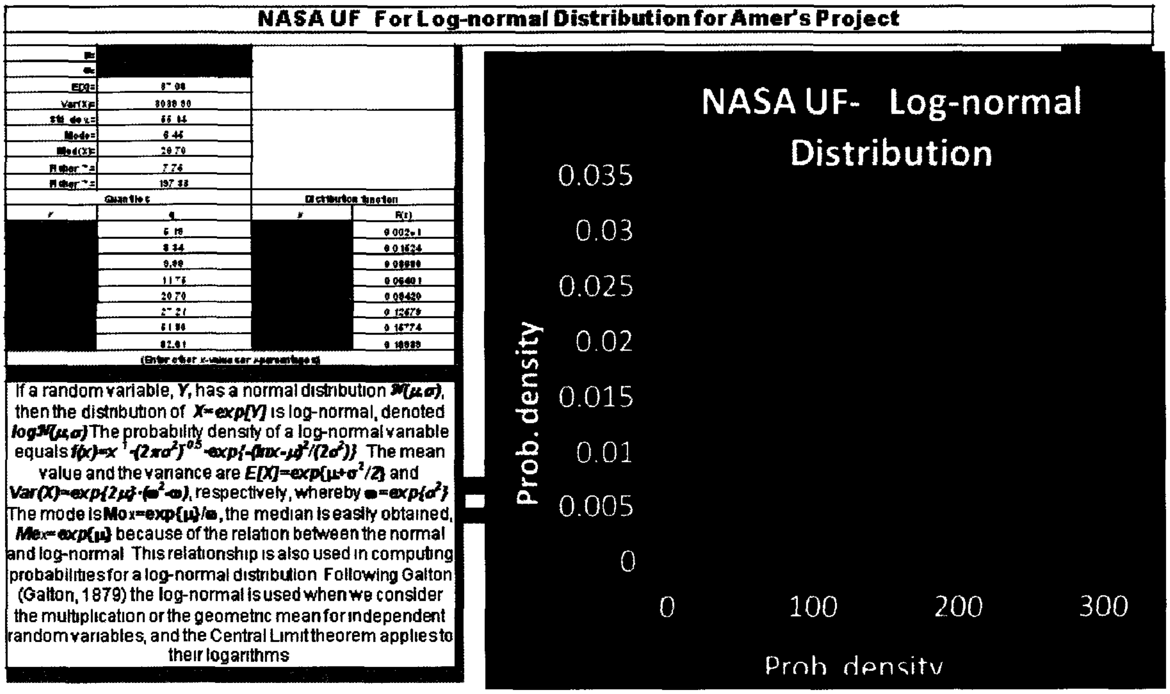


Figure 56. NASA Lognormal Distribution Model

Appendix I

NASA Uncertainty Factors

The NUFs listed below were developed as part of this research paper. This table should be used with the NASA lognormal model from Appendix H.

Table 20. NUFs Developed from this Research Project

Level of Risk	*NASA Uncertainty Factors*			
	None – Risk Adjusted	*Conservative*	*Semi-Aggressive*	Aggressive
Moderate (10-30%)	1	1.1	1.2	1.3
High (30-75%)	1	1.3	1.5	1.75
Very High (>75%)	1	1.75	2.1	2.5

Appendix J

NASA Joint Confidence Level Paradox – A History of Denial

Historical Cost and Schedule Growth Data Set

Compiled Cost & Schedule Growth Data Set

The following cost and schedule growth data is a combined list of the earliest available and latest available data for 188 projects. Some of the names are the same, but supplementary data led us to believe they were separate projects. In fact they may not be, renaming, rebaselineing, and whitewashing make this type of data mining and analysis very difficult. All data comes from reputable sources, however errors probably exist, and some projects are still in development, so values may continue to evolve.

It shows an average cost growth of 98.2%, a median cost growth of 53.3%, and average schedule growth of 56 8%, and a median schedule growth of 34 9%. This is abysmal to say the least and exceeds many of the recently published papers values **This data was not obtained until after paper was completed, so none was used in our analysis, but is included in an attempt to aide future researchers.**

Theme	Name	Initial	Latest Available	Percent change	Initial Schedule	Final Schedule	Percent Change
Heliophysics	ACE	$ 141 10	$ 108 50	-23 1%	57	62	8 2%
Earth Sci	ACRIMSAT				43	45	4 7%
	ACTS	$ 354 00	$ 656 00	85 3%	48	98	104 2%
	AFE	$ 159 00	$ 387 00	143 4%	Canceled		
	AHMS	$ 55 00	$ 55 00	0 0%			
Heliophysics	AIM	$ 61 10	$ 81 20	32 9%	40	50	24 7%
	Apollo	$7 000 00	$ 25 400 00	262 9%			
Earth Sci	Aqua	$ 762 50	$ 1 006 00	31 9%	89	107	19 4%
Earth Sci	Aquarius				50	69	38 0%
Manned	ASRM	$1,506 70	$ 3 251 80	115 8%	Canceled		
Manned	ATP	$ 372 00	$ 1 053 00	183 1%			
	AURA	$ 524 00	$ 763 00	45 6%	114	133	17 4%
Earth Sci	Aura (Chem-1) or Chemistry				41	60	46 3%
	AXAF	$1 410 00	$ 6,022 00	327 1%			
Heliophysics	BARREL					54	
Earth Sci	CALIPSO	$ 68 20	$ 170 3	149 7%	38	89	135 4%
Planetary	Cassini	$1 436 40	$ 1,375 90	-4 2%	92	110	19 6%
Manned	CAU	$ 442 00	$ 454 00	2 7%			
ASO	Chandra				69	79	14 5%
ASO	CHIPSAT				30	40	33 3%
Heliophysics	CINDI				41	95	131 7%
Manned	CLCS	$ 175 00	$ 399 00	128 0%	Canceled		
	Clementine					19	
Earth Sci	CloudSat	$ 80 20	$ 144 00	79 6%	36	85	136 6%
	Cluster				75	81	8 0%
Heliophysics	Cluster-2 (Rumba & Tengo)					131	
Heliophysics	Cluster-2 (Salsa & Samba)				75	130	73 3%
ASO	COBE				68	88	29 4%
Planetary	CONTOUR	$ 69 10	$ 96 80	40 1%	38	40	4 2%
	Cosmic Background Explorer	$ 97 50	$ 159 70	63 8%			
	COSTR	$ 221 00	$ 673 00	204 5%			
	CRAF	$3,593 00	$ 3 351 00	-6 7%	Canceled/ Development		
Earth Sci	CRRES				38	86	126 3%
	DART				31	43	38 7%
Planetary	DAWN	202 8	287 1	41 6%	37	53	43 2%
	Deep Impact	$ 194 10	$ 252 00	29 8%	44	63	43 9%
Planetary	Deep Space 1	$ 73 30	$ 99 30	35 5%	33	43	28 5%
	DSMS					36	
Earth Sci	EO-1	$ 72 00	$ 158 1	119 6%	33	58	74 2%
	ERAST	$ 181 30	$ 173 00	-4 6%			
	ESSP	$ 145 10	$ 171 80	18 4%			

	ET	$ 349 60	$ 961 70	175 1%			
ASO	EUVE	$ 107 40	$ 322 00	199 8%	48	58	20 8%
Heliophysics	FAST	$ 32 50	$ 42 90	32 0%	44	89	101 1%
	FCF	$ 118 90	$ 114 10	-4 0%			
	FTS	$ 317 00	$ 485 00	53 0%	Canceled		
	FTS	$ 317 00	$ 453 20	43 0%			
ASO	FUSE	$ 85 90	$ 143 7	67 3%	44	107	143 2%
ASO	GALEX	$ 41 10	$ 87 10	111 9%	37	60	61 4%
Planetary	Galileo Orbiter				43	136	216 3%
Planetary	Galileo Probe				43	136	216 3%
Planetary	Galilleo	$ 276 20	$ 1 639 00	493 4%			
Earth Sci	Genesis	$ 126 10	$ 162 90	29 2%	34	46	34 9%
Heliophysics	Geospace RBSP					44	
Heliophysics	Geotail				58	58	0 0%
	GGS	$ 334 00	$ 649 00	94 3%			
ASO	GLAST				66	93	40 9%
Earth Sci	Glory				88	106	20 5%
	GOES	$ 554 60	$ 1,241 00	123 8%			
	GOES	$ 691 00	$ 1,787 00	158 6%			
Earth Sci	GOES I				45	102	126 7%
Earth Sci	GOES J				53	115	117 0%
Earth Sci	GOES K				57	138	142 1%
Earth Sci	GOES L				65	175	169 2%
Earth Sci	GOES M				74	189	155 4%
Earth Sci	GOES N				41	96	134 1%
Earth Sci	GOES O				47	126	168 1%
Earth Sci	GOES P				83	137	65 1%
ASO	GP-B	$ 351 00	$ 709 30	102 1%	74	128	72 7%
Earth Sci	GPM				113	149	31 9%
Earth Sci	GRACE	$ 79 30	$ 88 40	11 5%	42	60	43 8%
Planetary	GRAIL				8	44	450 0%
	GRO	$ 183 80	$ 677 00	268 3%			
ASO	GRO - (Compton Gamma Ray Ob)				62	127	104 8%
	HESSI	$ 32 00	$ 63 50	98 4%	31	51	61 9%
ASO	HETE	$ 8 40	$ 23 50	179 8%	37	49	34 2%
	HST	$ 435 00	$ 1,682 00	286 7%			
ASO	HST SI				64	140	118 8%
ASO	HST SSM				70	146	108 6%
ASO	HST-OTA	$ 115 80	$ 561 70	385 1%	70	146	108 6%
Heliophysics	IBEX				33	36	9 1%
Earth Sci	ICESAT	$ 121 30	$ 177 00	45 9%	43	73	70 7%
Heliophysics	IMAGE	$ 83 60	$ 89 20	6 7%	42	49	15 5%
ASO	INTEGRAL	$ 8 20	$ 11 90	45 1%			
Earth Sci	JASON	$ 77 50	$ 87 80	13 3%	70	94	34 3%
Planetary	JUNO				51	51	0 0%
ASO	JWST	$ 900 00	$ 4,900 00	444 4%	92	114	23 9%
ASO	Kepler				48	64	33 3%
	LADEE					38	
Earth Sci	Landsat 7	$ 387 10	$ 508 80	31 4%	55	80	44 7%
	LANDSAT-D	$ 260 10	$ 538 00	106 8%			

	LCROSS				27	28	3 7%
Earth Sci	LDCM				38	38	0 0%
ASO	LISA				55	120	118 2%
SSE	LRO				38	39	2 6%
Manned	LTMCC	$ 87 10	$ 76 90	-11 7%			
Planetary	Lunar	$ 56 20	$ 56 60	0 7%	30	34	10 7%
Planetary	MAGELLAN	$ 322 80	$ 856 00	165 2%	61	73	19 7%
	MAP	$ 88 30	$ 94 20	6 7%	56	64	14 4%
ASO	MAP or WMAP				54	61	13 0%
Planetary	MPL				45	46	2 2%
Planetary	MCO	$ 183 60	$ 189 70	3 3%	39	45	16 6%
	MEDS	$ 201 70	$ 210 10	4 2%			
Planetary	MER	$ 499 40	$ 767 00	53 6%	34	34	1 1%
Planetary	MER-A or MER03 - SPIRIT)				35	35	0 0%
Planetary	MER-B (Opportunity)				35	36	2 9%
Manned	MERCURY	$ 196 92	$ 384 00	95 0%			
Planetary	Messenger	$ 191 50	$ 288 70	50 8%	46	57	23 7%
Planetary	MGS	$ 140 20	$ 130 70	-6 8%	31	34	8 7%
Planetary	MMM				31	35	12 9%
Heliophysics	MMS				85	85	0 0%
Planetary	MRO	$ 334 40	$ 450 0	34 6%	43	47	9 4%
Planetary	MSL	$ 650 00	$ 2,300 00	253 8%	45		
Planetary	NEAR	$ 150 00	$ 124 90	-16 7%	29	29	0 0%
Planetary	New Horizons				44	44	0 0%
	NMP	$ 111 70	$ 176 40	57 9%			
Earth Sci	NPP				79	123	55 7%
	NSCAT	$ 100 40	$ 255 00	154 0%			
ASO	NuStar					37	
Planetary	Mars Observer	$ 306 00	$ 994 00	224 8%	100	126	26 0%
Earth Sci	OCO				52	67	28 8%
Planetary	ODYSSEY	$ 267 20	$ 366 10	37 0%	33	34	3 0%
Manned	OMV	$ 236 00	$ 814 00	244 9%	Canceled		
Earth Sci	OSTM				72	74	2 8%
Planetary	PATHFINDER	$ 150 00	$ 174 20	16 1%	38	49	30 6%
Planetary	Phoenix/Scout 7				41	41	0 0%
Earth Sci	QUICKSCAT				14	21	50 0%
Heliophysics	RHESSI was HESSI				31	53	71 0%
	Rosetta	$ 28 40	$ 40 10	41 2%			
Heliophysics	Sampex				37	38	2 7%
Heliophysics	SDO				52	68	30 8%
	SeaWinds	$ 130 20	$ 148 80	14 3%			
Heliophysics	SET-1				39	89	128 2%
ASO	SIM				73	191	161 6%
Manned	SLWT	$ 172 50	$ 129 00	-25 2%			
Heliophysics	SNOE				23	35	52 2%
ASO	SOFIA	$ 234 80	$ 840 00	257 8%	48	207	331 3%
Heliophysics	SoHO				63	72	14 3%
	Solar Orbiter					84	
Heliophysics	Solar B or HINODE	$ 99 30	$ 80 40	-19 0%	58	83	43 1%
Earth Sci	SORCE	$ 68 00	$ 74 50	9 6%	32	55	71 6%

Manned	Shuttle	$5,800 00	$ 17,789 00	206 7%			
Manned	Shuttle – With Reserves	$6,960 00	$ 17,789 00	155 6%			
Manned	Shuttle – Endeavor	$2,100 00	$ 1,800 00	-14 3%			
Manned	SSME	$1,267 10	$ 3,051 50	140 8%			
Manned	Space Station	$9,446 24	$ 45,000 00	376 4%			
ASO	SIRTF or Spitzer	$ 472 00	$ 712 00	50 8%	55	88	60 1%
Manned	SRM	$ 338 60	$ 706 70	108 7%			
Manned	SS	$ 25 12	$ 28 94	15 2%			
Heliophysics	ST-5	$ 26 30	48 7	85 2%	48	78	62 5%
Heliophysics	ST-6					56	
ASO	ST-7				47	89	89 4%
Heliophysics	ST-8				37	32	-13 5%
CT	ST-9				42	42	0 0%
Planetary	STARDUST	$ 117 80	$ 126 4	7 3%	35	39	10 9%
	STDRS	$ 341 40	$ 532 00	55 8%			
Heliophysics	STEREO	$ 150 00	$ 550 00	266 7%	49	77	57 1%
ASO	SWAS	$ 47 30	$ 78 90	66 8%	57	116	104 2%
	SWASTR	$ 140 00	$ 212 70	51 9%			
ASO	SWIFT	$ 102 40	$ 164 90	61 0%	41	60	45 1%
	TDRS7	$ 269 00	$ 532 00	97 8%			
	TDRS-H				41	52	26 8%
	TDRS-I				47	73	55 3%
	TDRS-J				53	82	54 7%
	TE	$ 321 30	$ 401 50	25 0%			
Earth Sci	TERRA	$1,078 70	$ 1,393 20	29 2%			
Earth Sci	Terriers				31	56	80 6%
	Tether	$ 28 30	$ 115 70	308 8%			
Heliophysics	THEMIS	$ 102 30	$ 107 60	5 2%	37	44	17 6%
Heliophysics	TIMED	$ 129 20	$ 176 20	36 4%	44	86	97 1%
	TOPEX	$ 438 00	$ 520 00	18 7%			
Earth Sci	Topex/Poseidon				105	151	43 8%
Heliophysics	TRACE	$ 35 60	$ 40 30	13 2%	26	52	101 2%
	TRDS	$ 899 80	$ 803 10	-10 7%			
	Triana Spacecraft	$ 75 00	$ 96 90	29 2%			
Earth Sci	TRMM	$ 218 80	$ 468 00	113 9%	72	87	21 0%
	TSS	$ 40 70	$ 263 00	546 2%			
Earth Sci	UARS	$ 575 30	$ 790 00	37 3%	73	95	30 1%
Heliophysics	Ulysses	$ 196 00	$ 460 00	134 7%	40	132	230 0%
Heliophysics	WIND				48	71	47 9%
ASO	WIRE	$ 39 70	$ 50 70	27 7%	44	57	30 7%
ASO	WISE				42	59	40 5%
Manned	X-30	$3,100 00	$ 10,000 00	222 6%	Canceled		
Manned	X-33 - Canceled	$1 075 20	$ 1 789 70	66 5%	Canceled		
Manned	X-34 - Canceled	$ 70 00	$ 378 00	440 0%	Canceled		
Manned	X-38 - Canceled	$ 500 00	$ 1,500 00	200 0%	Canceled		
Manned	X-43 Hyper-X Canceled	$ 167 00	$ 227 00	35 9%	Canceled		
ASO	XTE or RXTE	$ 100 00	$ 373 00	273 0%	53	48	-9 4%

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PATENT/ INVENTIONS

- The Thermal Conductivity of Thin Films System - U.S. Patent # 6331075, issued December 18, 2001.

SPECIAL RECOGNITIONS

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