Using Historical NASA Cost and Schedule Growth to Set Future Program and Project Reserve Guidelines

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Abstract

By looking at historical schedule and cost growth, the past can be used to established reserve guidelines for future missions. This paper looks at recent NASA cost and schedule growth history, categorizes the reasons for growth, isolates growth due to external programmatic reasons versus internal technical reasons, assesses relationships for causality and provides guidance for the proper cost and schedule reserves to be carried at both the Program and Project levels. Mission cost and schedule growth history from both planetary and Earth-orbiting programs, such as Mars Exploration, Discovery, Medium and Small Explorer, Earth System Science Pathfinder, New Millennium and others, are investigated. The reserve guidelines developed are compared to industry standard guidelines and rules of thumb to determine if these standard practices continue to be valid.

1 Introduction

This paper investigates recent NASA cost and schedule growth history for forty science missions. These missions included both Space and Earth Science missions and covered Programs such as Mars Surveyor and Exploration, Discovery, Medium and Small Explorer (MIDEX/SMEX), Earth System Science Pathfinder (ESSP), New Millennium and others. An examination of this historical data has shown that such space projects often experience schedule delays and higher costs relative to initial estimates and project plans. The reasons for these delays and increased cost may be varied, but for the purposes of this paper, the authors attempt to isolate and categorize these reasons, as either internal or external. Internal growth factors are classified as within the Project's control, and are either technical or programmatic in nature. Internal technical growth may be related to instrument development challenges, whereby internal programmatic growth may be due to an inability to properly staff an activity. External growth factors are categorized as growth associated with launch vehicle problems, funding restrictions, etc, and deemed as outside the Project's immediate control. A number of organizations, such as the United States General Accounting Office (GAO), and the Congressional Budget Office (CBO), have also attempted to study the cost and schedule growth of NASA missions in the past, and quantify the effects.[1,2,3] Investigating historical schedule and cost growth, categorizing the reasons for growth, and assessing the causal relationships has gleaned some insights about reserve guidelines and practices that are summarized and described in the paper. Disclaimer: These data were examined and the authors made certain assumptions in terms of growth classifications deemed reasonable based on the available public sources. The authors would be happy to accept new data and inputs for review.

2 Study Approach

To provide an assessment of potential required reserve levels, an assessment of historical cost and schedule growth was undertaken. The primary source of information for the basis for cost and schedule growth is the NASA Fiscal Year Budget Estimates from 1992 to 2007. These documents are publicly released in February of each year and display the cost and major milestones of NASA's major programs. An example of the cost as reported is shown in Figure 1 while the reporting of the major milestones is shown in Figure 2. The example shown in each figure is for the Genesis mission for Fiscal Year 2000 (FY00) as reported in February 1999. The data shown in Figure 1 for FY00 represents the actual cost of the mission for years

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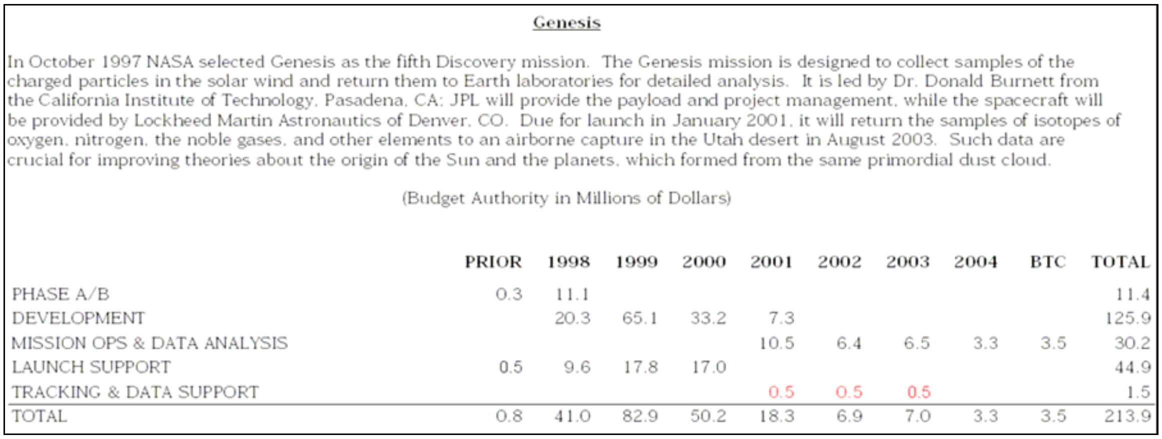
prior to 1999, the cost for 1999 represents a forecast based on the best estimate for the current year, while the year 2000 and beyond represents the planning budget for the remainder of the mission. All data is shown and compared in Real-year dollars. Similarly the major milestones shown in Figure 2 identify the planned and actual milestones for the mission.

For the purposes of this study, cost growth was measured from the initial project budget submittal to final actual cost of the mission. As defined in this paper, cost growth was only measured for the development cost of the mission, including Phase A and B cost, excluding mission operations and data analysis, launch support and tracking and data support cost. Additionally, schedule growth was measured from the schedule as defined by the start of Phase B until launch for the initial, planned project schedule as compared to final duration of the schedule based upon the actual launch date. For the example shown in Figures 1and 2, the initial development cost for Genesis is calculated as the sum of the Phase A/B and Development cost of $137.3M while the development duration is from the start of Phase B, assumed to be November 1997 after a October 1997 selection, until the planned launch date of January 2001 for a planned mission development time duration of 39 months. All subsequent growth is measured from these initial numbers. Where possible, the increase in cost due to application of full cost accounting in FY04 was removed from the total mission cost for the purpose of comparison.



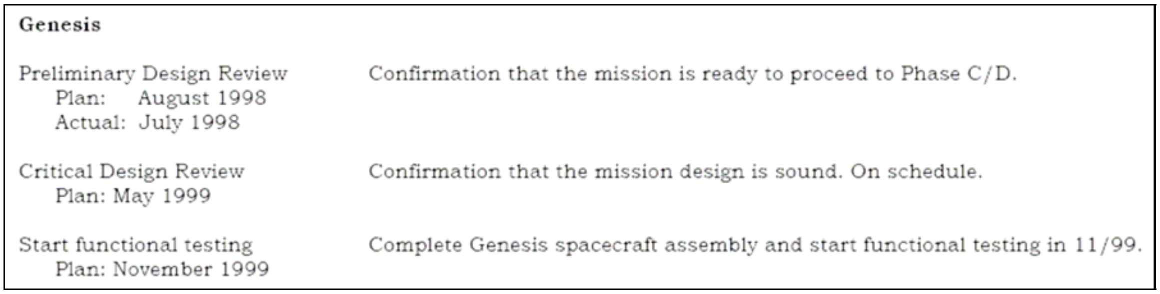
Genesis

In October 1997 NASA selected Genesis as the fifth Discovery mission. The Genesis mission is designed to collect samples of the charged particles in the solar wind and return them to Earth laboratories for detailed analysis. It is led by Dr. Donald Burnett from the California Institute of Technology, Pasadena, CA; JPL will provide the payload and project management, while the spacecraft will be provided by Lockheed Martin Astronautics of Denver, CO. Due for launch in January 2001, it will return the samples of isotopes of oxygen, nitrogen, the noble gases, and other elements to an airborne capture in the Utah desert in August 2003. Such data are crucial for improving theories about the origin of the Sun and the planets, which formed from the same primordial dust cloud.

(Budget Authority in Millions of Dollars)

	PRIOR	1998	1999	2000	2001	2002	2003	2004	BTC	TOTAL
PHASE A/B	0.3	11.1								11.4
DEVELOPMENT		20.3	65.1	33.2	7.3					125.9
MISSION OPS & DATA ANALYSIS					10.5	6.4	6.5	3.3	3.5	30.2
LAUNCH SUPPORT	0.5	9.6	17.8	17.0						44.9
TRACKING & DATA SUPPORT					0.5	0.5	0.5			1.5
TOTAL	0.8	41.0	82.9	50.2	18.3	6.9	7.0	3.3	3.5	213.9

Figure 1: Genesis Fiscal Year 2000 Project Budget



Genesis

Preliminary Design Review Plan: August 1998 Actual: July 1998	Confirmation that the mission is ready to proceed to Phase C/D.
Critical Design Review Plan: May 1999	Confirmation that the mission design is sound. On schedule.
Start functional testing Plan: November 1999	Complete Genesis spacecraft assembly and start functional testing in 11/99.

Figure 2: Genesis Fiscal Year 2000 Major Milestones

Additionally, the major milestones report provides an explanation when a major milestone is delayed. The explanation of the delay provides the basis for categorizing the schedule delay as either internal growth, which should have been under the project's control, versus external growth, which is outside of the project's control. The specific types of factors contributing to growth are explained further in section 3.2.

3 Explanation of Data

Data for forty NASA missions were used as the basis for the cost and schedule growth. These missions included both Space and Earth Science missions and covered Programs such as Mars Surveyor and

Exploration, Discovery, Medium and Small Explorer, Earth System Science Pathfinder, New Millennium and others. The missions assessed within the study are shown in Table 1.

Table 1: List of Missions Included in the Study

- Discovery
  - Lunar Prospector
  - Mars Pathfinder*
  - NEAR*
  - Stardust*
  - Genesis
  - Contour*
  - Messenger
  - Deep Impact
- Mars Exploration
  - MGS*
  - MCO/MPL*
  - MER*
  - MRO*
- New Millennium
  - EO-1
  - DS-1
- Explorer
  - FAST
  - TRACE
  - SWAS
  - WIRE
  - ACE
  - FUSE
  - IMAGE
  - MAP
  - HESSI
  - GALEX
  - SWIFT
  - HETE-II
  - THEMIS
- Solar Terrestrial Probe
  - TIMED
  - STEREO
- ESSP
  - GRACE
  - CALIPSO
  - CLOUDSAT
- Great Observatory Class
  - Spitzer (SIRTF)
  - Gravity Probe B
- Flagship
  - EOS-Aqua
  - EOS-Aura
  - TRMM
- Other
  - LANDSAT-7
  - SORCE
  - ICESAT

3.1 Restricted versus Non-Restricted Missions

The eight missions identified with an asterisk in Table 1 had a restricted launch window in which, due to planetary alignment constraints or specific intercept trajectory requirements, they must be launched by a given date. This is true of all Mars missions where a missed launch opportunity results in a delay of 26-months until the next launch opportunity presents itself. It should be noted that, although the Deep Impact, Messenger and Deep Space-1 (DS-1) are all non-Earth Orbiting missions, they all launched after their initial, scheduled launch dates using alternative launch windows and are therefore not considered restricted missions.

It is important to separate the restricted versus non-restricted missions as the restricted missions are not allowed to have schedule growth, as such growth would translate into the absolute loss of the mission opportunity. Although they do experience cost growth, in many cases this cost growth is limited, as will be discussed in Section 4, as only a finite amount of additional effort can be applied before the mission must be launched. The additional schedule pressure can be problematic, however, as previous studies have shown that the schedule pressure experienced by missions with restricted launch windows can lead to a higher rate of mission failure.[4]

3.2 Internal versus External Factors Driven-Growth

Growth is defined either as an internal growth, which should have been under the project's control, or external growth, which is considered outside of the project's control. Figure 3 identifies the distribution of internal versus external growth for the missions investigated. The figure shows that only five missions from the complete data set (12.5%) showed no growth while only eight missions (20%) showed growth caused by purely external forces. This suggests that it is very difficult for missions to manage to their cost and schedule budgets even though forces solely outside of their control cause only 20% of the growth.

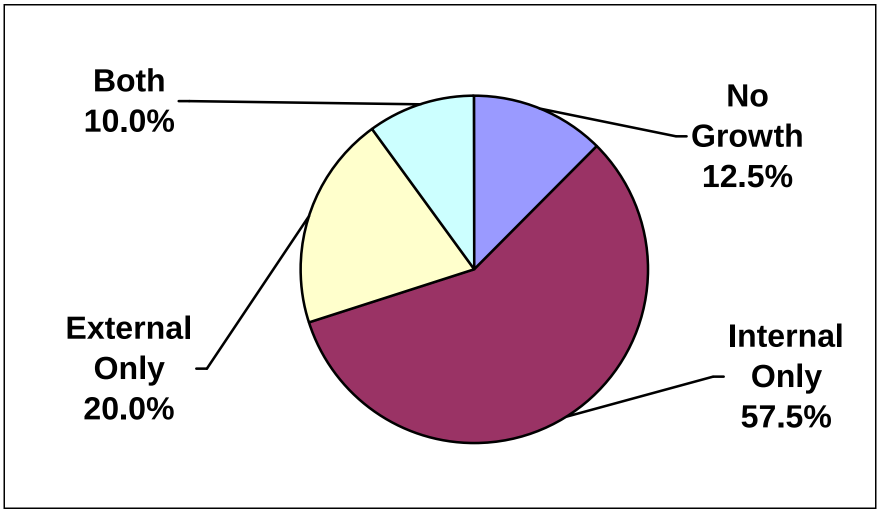


Figure 3: Distribution of Internal versus External Growth

Internal Growth is classified as related to instrument technical development challenges, spacecraft technical problems, growth due to test failures, growth due to overly optimistic heritage assumptions and growth due to management problems such as staffing issues or other inefficiencies. External growth is categorized as growth associated with launch vehicle problems, funding restrictions that stretched out a mission or other problems such as natural disasters, unexpected failure of test equipment, additional programmatic requirements levied upon the project or other factors that are outside of the project's control.

Of the forty missions investigated, eighteen had some form of instrument problems, classified as an internal growth, that caused an eventual launch delay. Figure 4 identifies the type of internal growth as a percentage of all internal growth. The data again indicates that instrument problems are the largest contributor to project cost and schedule growth.

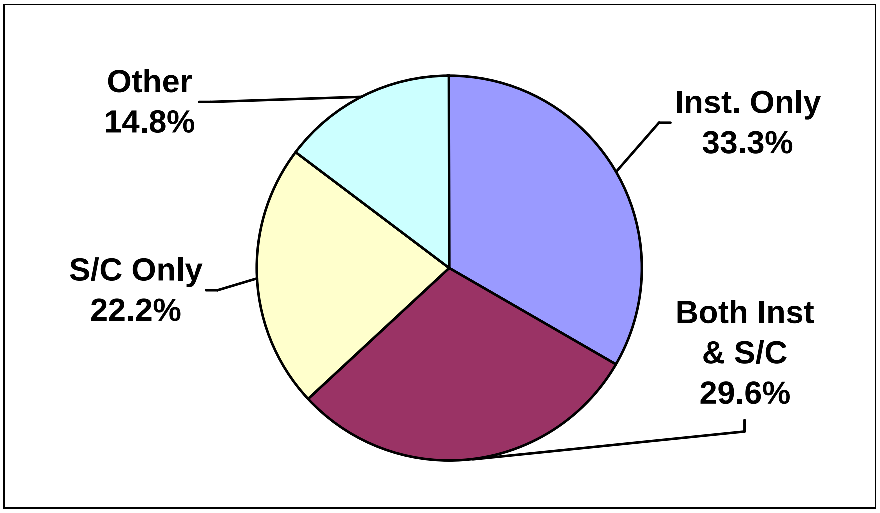


Figure 4: Distribution of Internal Growth

The primary contributor to external growth is problems from the readiness of the launch vehicle. Of the forty missions investigated, ten of the launch dates of the missions were delayed, leading to subsequent cost growth, due to launch vehicle delays. Of the launch vehicle-related growth, almost all were caused by smaller launch vehicles such as the Athena, Pegasus and Taurus launch vehicles or the dependence upon a foreign launch vehicle. Figure 5 identifies the type of external growth as a percentage of all external growth.

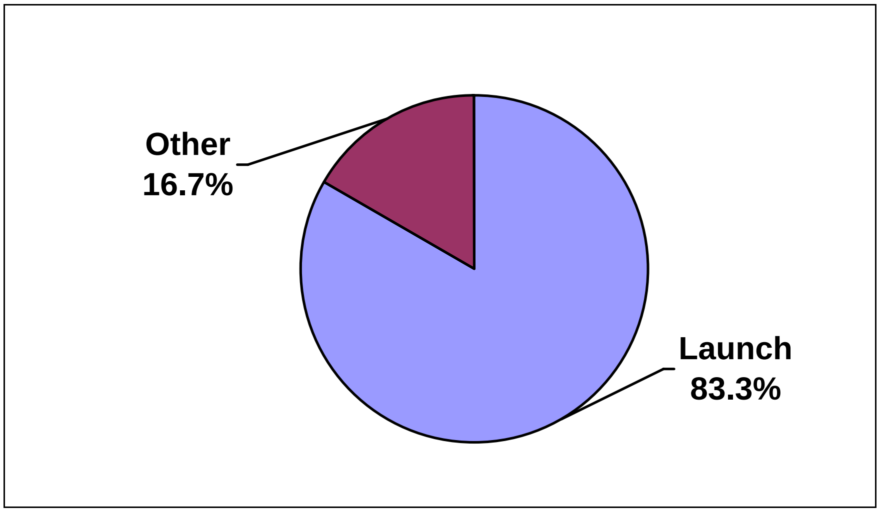


Figure 5: Distribution of External Growth

4 Historical Cost and Schedule Growth

An examination of this historical data has shown that space projects often experience schedule delays and higher costs relative to initial estimates and project plans. The reasons for these delays and increased cost may be varied, but the majority of the reasons, as shown in Section 3, appear to be internal growth that should be within the project's management control.

4.1 Growth Summary

The forty space missions and the summary of development cost and schedule are captured on Figures 6 and 7, respectively. A mission with no cost or schedule growth would be represented by the y=x line, a slope of 1, and be perfectly correlated; this is represented by the dashed red line in Figures 6 and 7. It can be seen in both figures that, for the majority of missions, growth has occurred as indicated by the large amount of scattering in the data above the y=x dashed red line.

Figure 6 represents the mission cost growth, and illustrates the initial planned cost on the abscissa, and the final actual cost on the ordinate. For the mission data set, the average cost growth is 26.9%, with the median cost growth being 16.1%. The maximum cost growth for the data set was 150%, and the minimum cost growth for the data set was –21.4%.

Figure 7 represents the mission schedule growth, and illustrates the initial planned schedule on the abscissa, and the final actual schedule on the ordinate. For the mission data set, the average schedule growth is 21.5%, and the median schedule growth is 16.1%. The maximum schedule growth for the data set was 84.2%, and the minimum schedule growth was 0%. The range of absolute schedule growth was 0 months to 43.4 months, with an average of 11.6 months.

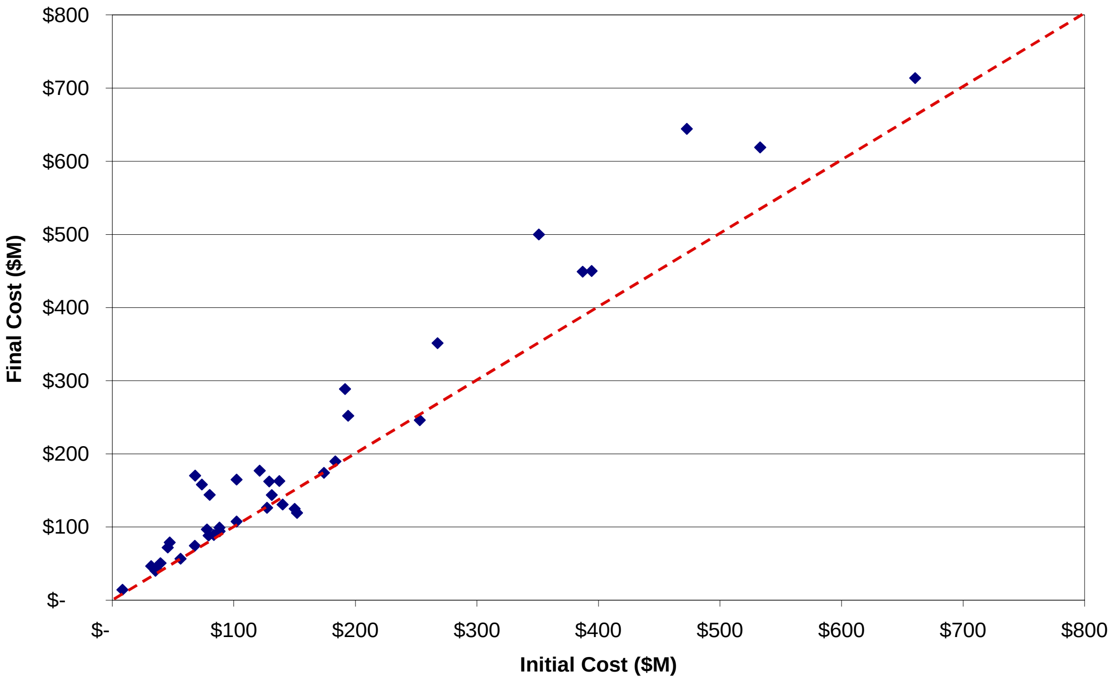


Figure 6: Summary of Initial versus Final Development Cost

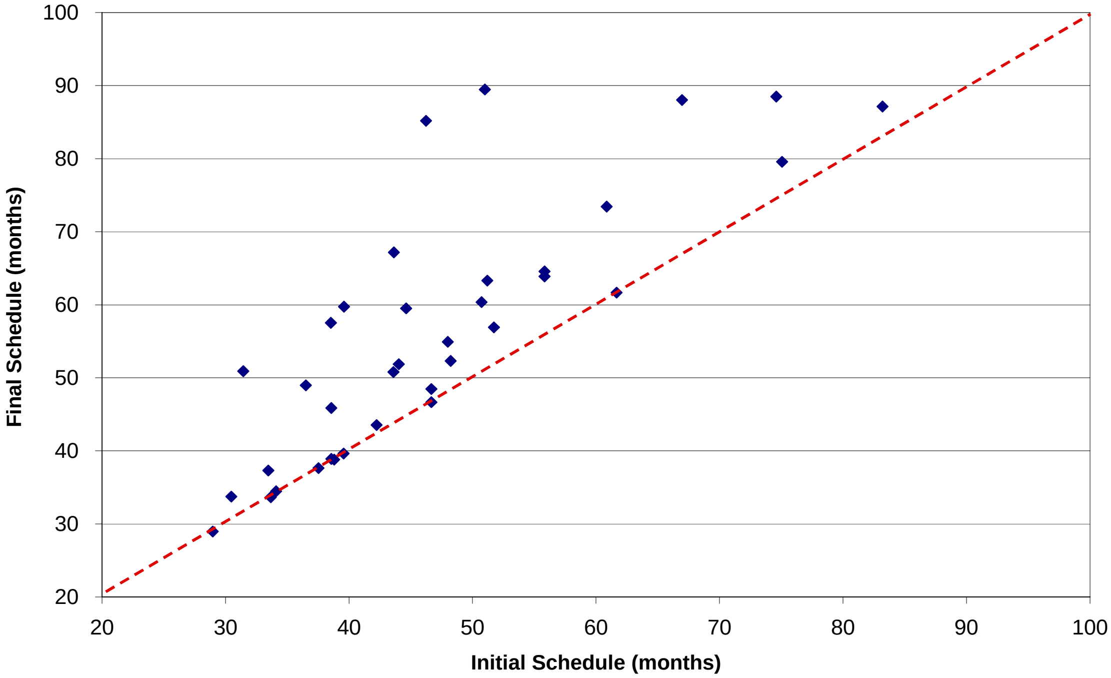


Figure 7: Summary of Initial versus Final Development Schedule

4.2 Classification

There are a myriad of ways that one could examine and classify the science mission data. From the public data sources that were reviewed, there were two key classes that immerged in the assessment. The first class was related to the type of cost and schedule growth experienced: internal versus external. The second class was in regards to whether there was any type of restriction on the mission launch date: restricted versus non-restricted. A discussion of these classifications and the key observations about cost and schedule growth follows.

4.2.1 Internal versus External Growth

As was described in Section 3.2, of the forty-mission data set, 27 missions (67.5 %) experienced internal growth, and 12 missions (30 %) experienced an external growth. Only 4 missions (10%) had both internal and external growth. Figure 8 illustrates the summary of internal versus external growth. For projects that experienced internal growth, growth *within* the project's management control, the average cost growth was 31.7%, and the average schedule growth was 21.2%. The range of absolute schedule growth for this set was 0 to 42.6 months, and the average absolute schedule delay was 11.5 months.

For projects that experienced external growth, growth *outside* the project's management control, the average cost growth was 22.0%, and the average schedule growth was 24.1%. The range of absolute schedule growth for this set was 0 to 43.4 months, and the average absolute schedule delay was 11.9 months. It is interesting to note that there is a significant amount of cost and schedule growth that occurs due to internal-related factors that are deemed within the project's realm of influence. For the four projects, which experienced both internal and external growth, the average cost growth was 79.8% and the average schedule growth was 53.2%. The range of absolute schedule growth for this set was 7.3 to 38.9 months, and the average absolute schedule delay was 24.3 months.

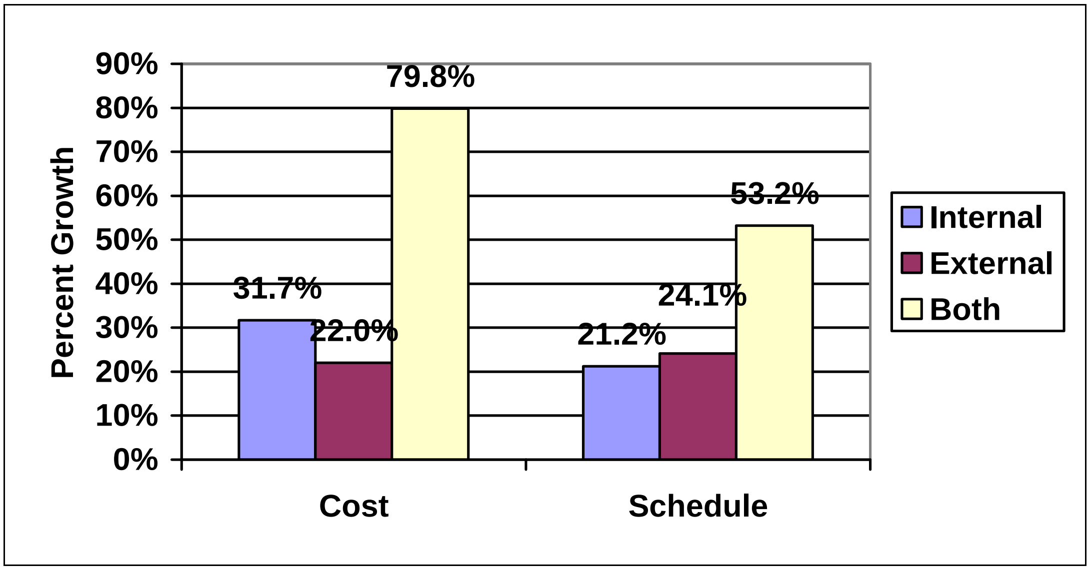


Figure 8: Summary of Internal versus External Growth

4.2.2 Restricted versus Non-Restricted

As was described in Section 3.1, of the forty-mission data set, 8 missions (20%) had a restricted launch window, and the rest (80%) were classified as having a non-restricted launch date. Figure 9 illustrates the summary of cost and schedule growth for restricted versus non-restricted missions. For projects that had restricted launch windows, the average schedule growth is 0.3%, and the average cost growth is 4.5%. The range of absolute schedule growth was 0 months to 0.4 months, with an average of 0.1 months. In contrast, for projects which had non-restricted launch windows, the average schedule growth is 26.8%, and the average cost growth is 32.6%, as illustrated in Figure 9. For this non-restricted mission set, the range of absolute schedule growth was 0 months to 43.4 months, with an average of 14.2 months.

The average schedule growth number for missions with restricted launch windows is intuitive; one would expect very limited schedule growth for these missions. However, the cost growth number is not as significant as what might be anticipated. For a project with fixed requirements and a fixed schedule, it is likely that cost will grow if development problems occur.[5] The question for discussion is "how much?" What is observed from this data set is that, although the missions do experience cost growth, in many cases this cost growth is limited, as only a finite amount of additional effort could be applied before the mission must be launched.

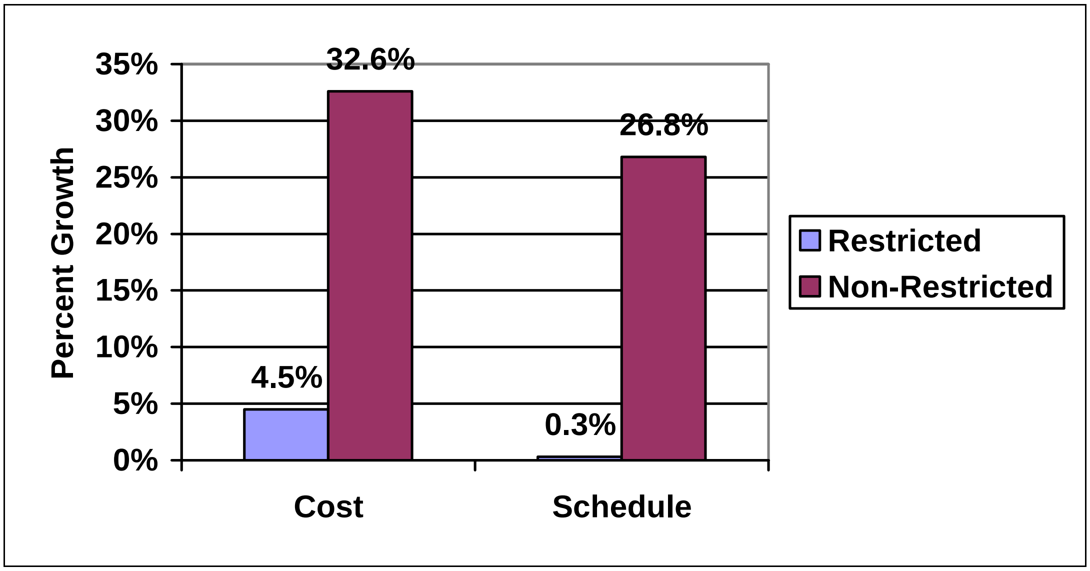


Figure 9: Summary of Growth of Restricted Launch Opportunity Missions vs. Non-Restricted

Moreover, three out of the eight restricted missions, Mars Pathfinder, Stardust, and NEAR, were operating in the early days of the Discovery Announcement of Opportunity (AO) process, and had performed well in terms of cost and schedule growth. Figure 10 illustrates the cost growth performance for missions started in the mid-90s versus missions started later, after 1998. The best-fit regression line has an R squared term of 0.76, meaning that the regression line explains 76 percent of the variation in the percent cost growth. For this restricted mission data set consisting of eight missions, there is a noticeable trend toward more cost growth in more recent missions. Observing the trend line for this data, missions starting after 1998 would have a greater than 10% resultant cost growth. There is no such noticeable trend in cost growth for the non-restricted mission data set as shown in Figure 11.

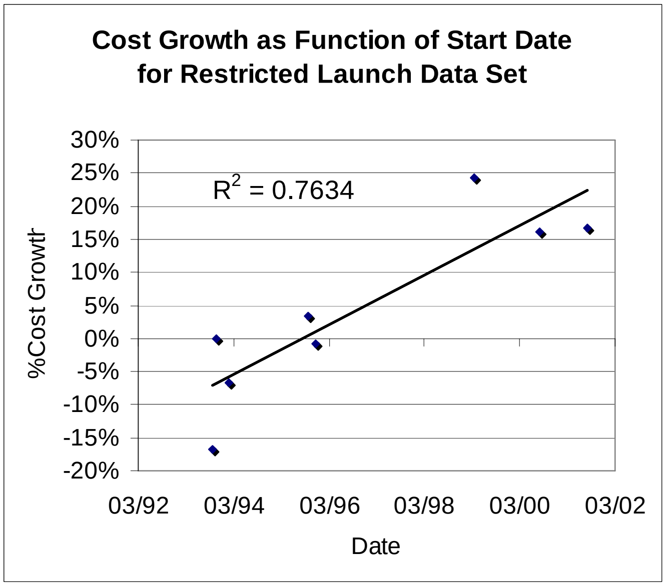


Figure 10: Cost Growth as a Function of Start Date for Restricted Launch Data Set

Finally, the failure rate is also higher for this restricted mission set, as two out of the eight missions experienced a complete loss of mission (25%), versus only one failure for the thirty two non-restricted missions (3%). This topic had been explored in detail in previous studies, which have shown that the schedule pressure experienced by missions with restricted launch windows can lead to a higher rate of mission failure.[6]

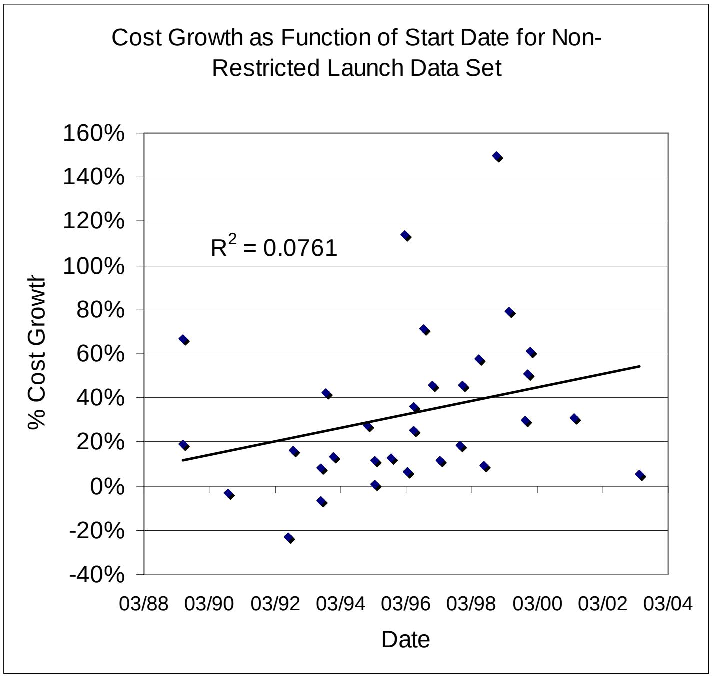


Figure 11: Cost Growth as a Function of Start Date for Non-Restricted Launch Data Set

4.3 Causal Relationships

Based on the significant number of missions that experienced cost and schedule growth, the primary question remains: what is the specific cause of the growth? It is understood that space systems are complicated and are always challenging but, given that these missions started in the early 1990s and that the Aerospace industry has been building space-based instruments and spacecraft for over 30 years, one would postulate that the estimates of the cost and schedule for the missions investigated should have more accurately predicted the eventual costs and schedules for these missions. In other words, less cost and schedule growth should have been experienced from these initial estimates. The following addresses potential causes for the cost and schedule growth experienced.

Inherent Optimism in Initial Design and Estimates

Estimating the development costs and associated development schedules of space-based systems is a challenging problem. In an environment where the lowest cost bidder often wins, a potential contractor is compelled to, as stated by then-NASA Administrator James Webb, "put his best foot forward".[7] The problem is not just limited to contractors as program and acquisition managers sometimes accept unrealistically low cost estimates to establish a budget they know will allow a program to be initiated. This paradigm results in optimistic budgets and cost proposals based on the desire of program managers to begin their programs and the contractors to win the award.

The Discovery Announcement of Opportunity (AO) process is a competitive selection in which proposers specify the scientific objectives and specific mission implementation approach while staying within a given cost cap and launching by a given launch date. Although initial Discovery missions such as Lunar Prospector, NEAR, Mars Pathfinder and Stardust performed well in terms of cost and schedule growth, subsequent mission have not faired as well. These initial missions were developed to meet specific cost and schedule constraints, and therefore were developed to fit "inside the box". In addition, these projects were managed to strict cost and schedule baselines yet still resulted in highly successful missions.[8,9,10]

The increasingly competitive nature of the Discovery AO process, however, may have caused missions to be proposed that, in order to win, are relatively optimistic in terms of their assumptions about heritage, technology development progress, required retesting or rework and cost and schedule efficiencies. Figure 12 identifies the average cost growth for Discovery missions from the initial selection of the first two Discovery missions in 1993 to the most recent selections. As can be seen, there is a significant growth trend, implying that the proposers' assumptions may have been more aggressive, and perhaps too optimistic, when competing for a Discovery mission. This growth trend is continuing with the Dawn and Kepler missions which experienced, and are continuing to experience, cost growth. [11,12] This trend may be reversing itself, however, as the 2004 Discovery AO process resulted in no full mission proposals being selected. As stated by Andrew Dantzler, then Acting Director of NASA's Solar System Division, NASA is looking for proposals in the next Discovery selection that will be "… commensurate with the technical complexities associated with Discovery class experiments".[13] A logical inference from this statement is that the mission proposals submitted were outside the scope of the cost and schedule constraints of a Discovery class mission.

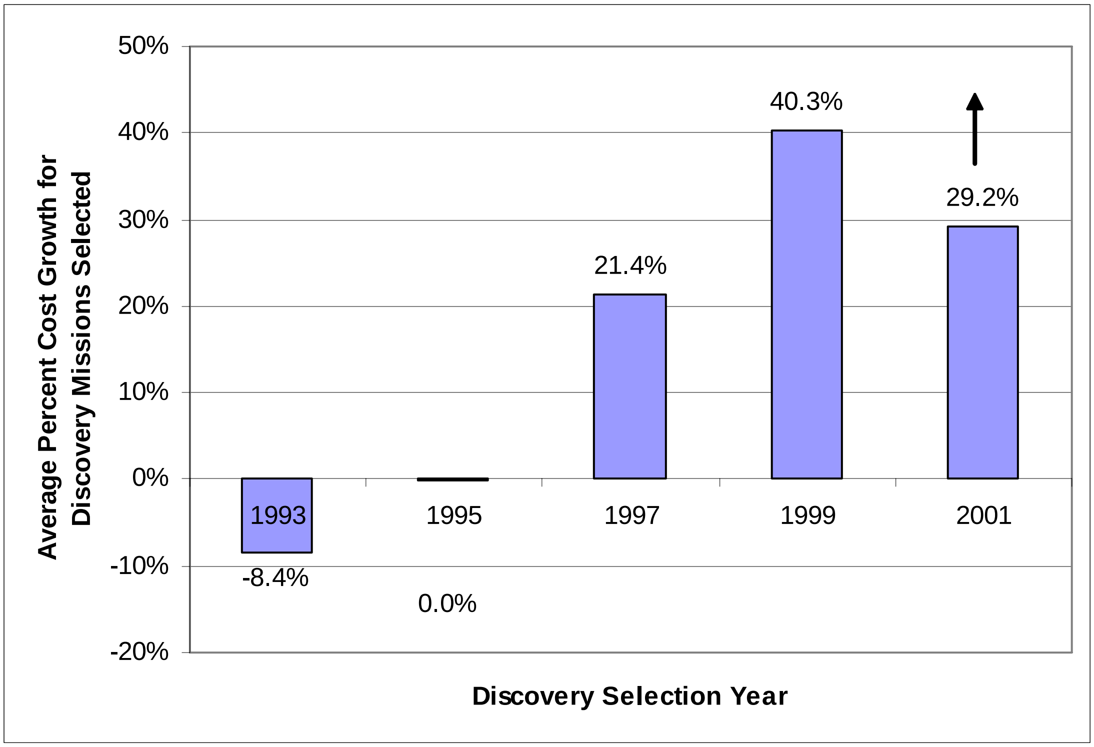


Figure 12: Progression of Average Cost Growth for Discovery Selections

This optimism is not constrained to the Discovery AO process as both the MIDEX and ESSP Programs have experienced their share of growth. Lessons learned from two missions that were cancelled due to cost growth, the MIDEX Full-sky Astrometric Mapping Explorer (FAME) mission and the ESSP Vegetation Canopy Lidar (VCL) mission, stated that optimistic cost and schedule assumptions, based on optimistic design and technology development assumptions, led to their cancellation.[14,15] As stated in the VCL Case Study, "Because Headquarters focused on the science and virtually ignored the underlying concerns about feasibility, management approach, and ability to perform within the proposed cost and schedule, the selection process didn't recognize VCL's flawed plans."[15]

Instrument Technical Problems

As shown previously in Figure 4, instrument development difficulties are the most prevalent form of internal problem. Figure 13 identifies the relative cost and schedule growth associated with problems resulting from the instrument only versus the spacecraft only versus problems with both the instrument and spacecraft. As can be observed, elimination of instrument problems would significantly reduce the cost growth experienced by projects. Typically an instrument is on the critical path for development, and any delay in the instrument results in a “marching army” cost that includes spacecraft, systems engineering, ground system, integration and test and other personnel. If the majority of instrument issues were resolved prior to the start of spacecraft development, missions should be able to be developed with less risk with the instruments able to be delivered and integrated to the spacecraft in a relatively short time. Two examples of this development approach are the QuikSCAT and QuickTOMS missions where the instruments for each, SeaWinds for QuikSCAT and TOMS for QuickTOMS, had already been largely developed. The resulting schedule for the spacecraft development was less than two years for both missions, which is significantly less than missions within the dataset.[16,17] Such a phased development strategy should be given consideration for mission developments. Although the authors have not shown that the cost for such a phased development approach would be less than if developed under more typical development approaches, it is certainly true that many of the unplanned marching army costs would be avoided when the instrument and spacecraft development activities are de-coupled. Since additional schedule translates into cost impact, such a phased development strategy, whereby the instrument is developed up-front and separately, should be given consideration as a viable development approach alternative.

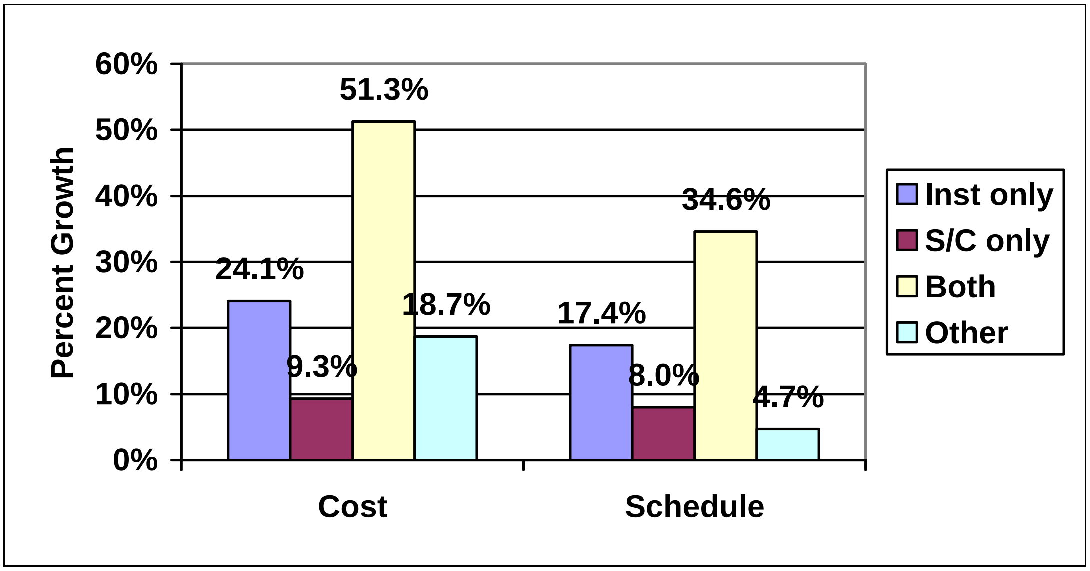


Figure 13: Cost and Schedule Growth due to Instrument, S/C and Other Problems

5 Interrelationship of Schedule & Cost Growth

Figure 14 shows the relationship between schedule growth and corresponding cost growth for non-restricted missions. As can be seen, for this data set, the best fit regression line is linear, with the equation, y = 1.23548x, resulting in an R squared term of 0.6124, meaning that the regression line explains 61% of the variation in the development time. The corresponding relationship states that for every 10% of schedule growth, there should be a corresponding 12% increase in cost growth. Although the variations can be significant, a general rule of thumb could be followed that states that for every percent of schedule growth, there will more than likely be an equal or greater percent of cost growth.

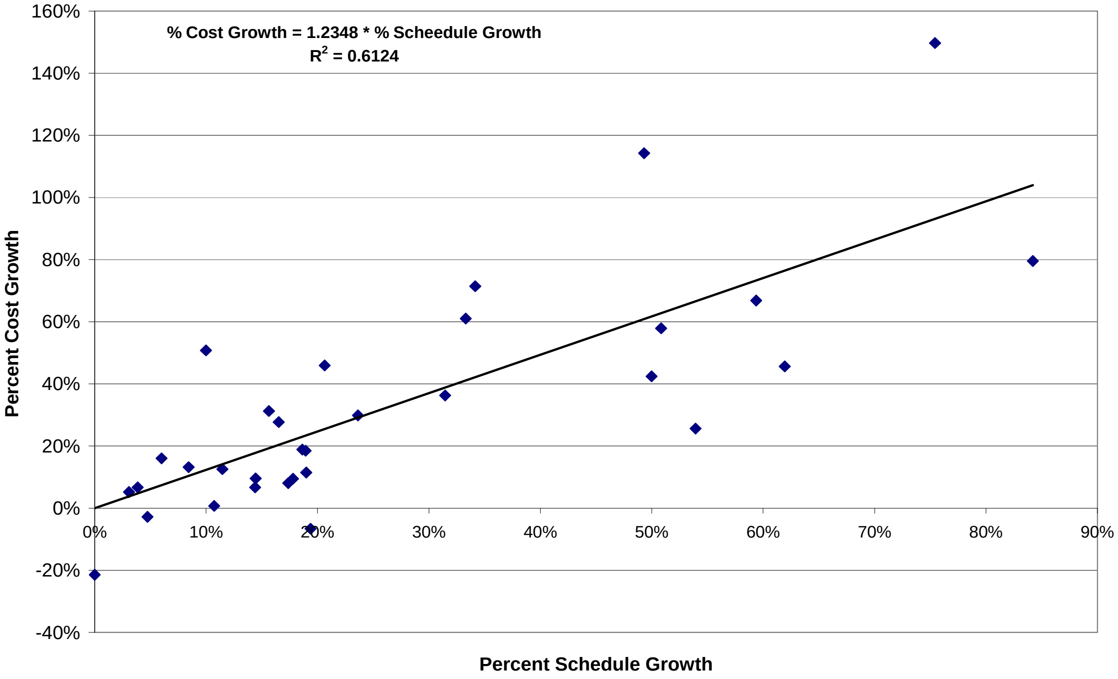


Figure 14: Interrelationship of Cost and Schedule Growth for Non-Restricted Projects

6 Cost and Schedule Reserve Guidelines

The previous sections identified the cost and schedule growth relative to the baseline cost and schedule. The baseline cost and schedule, however, included some level of reserves. When using NASA budget documents as a data source, however, reserve levels are not explicitly identified. Using NASA backup budget documents and other sources, reserve values for eighteen of the forty missions were obtained. The cost reserve levels held by each mission varied from 10 to 30% while the average reserve was on the order of 18%. Segmenting this dataset into the 5 restricted flight opportunity missions and 13 non- restricted missions, the restricted missions averaged 17.4% cost reserves and the non-restricted missions average 18.8% cost reserves, a difference deemed to be insignificant. Figure 15 shows the relationship, or lack thereof, between the initial cost reserves and the cost growth, over and above the reserves, experienced by the different missions. Although somewhat counter intuitive, this is consistent with other findings that also did not show a significant correlation.[18]

What can be discerned from the data, however, is that for the 5 missions in the 18 mission data set that had less than 5% cost and schedule growth, two of which had non-restricted launch windows, the average cost reserve was 18.6%. These missions demonstrate that it is feasible for a mission to manage to cost and schedule constraints given initial project reserves on the order of 19%.

Additionally, although specific schedule reserve could not be identified from the budget, a general industry rule of thumb that was prevalent when these missions were developed was that a mission should carry one-month of schedule reserve for each year of development. This equates to an 8.3% schedule reserve for the project.

This leads to the question of the proper levels of reserve. If the average cost reserve level is 19% and the average cost growth for the non-restricted missions as shown in Figure 9 is 33%, does this mean that a project should only be initiated with over 50% cost reserve? Additionally, if the assumed average schedule reserve level is 8% and the average schedule growth for these missions is 27%, does this mean that a project should be initiated with over 35% schedule reserve – i.e. four months of funded schedule reserve for every year of development? Hopefully, the answer to each question is "No" as a "Yes" answer implies that NASA cannot predict the cost of missions at their initiation with any degree of certainty.

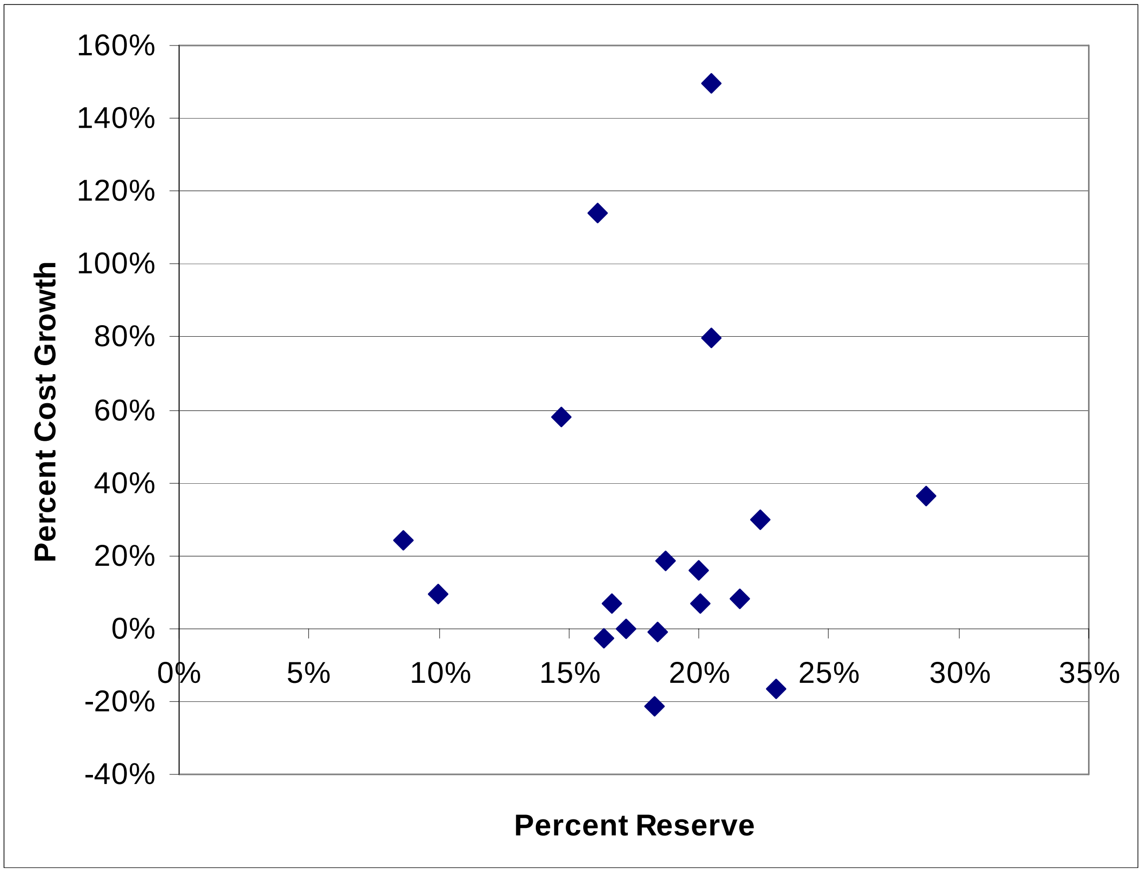


Figure 15: Initial Reserve Levels versus Cost Growth

In Section 4.3, the authors postulated that some of the potential causes for cost and schedule growth were due in particular to inherent optimism in initial design and estimates, as well as instrument technical difficulties. In the following section, cost and schedule growth data were further examined, utilizing another segmentation, to provide guidance from which the "revised" reserve guidelines were gleaned.

6.1 Recommendations based on Historical Data

To address the question of the proper levels of reserves, the authors have tried to segregate the data to determine a recommended reserve level based upon historical results. In order to determine the proper levels of reserve to be held at the Project level versus the Program level, growth relative to internal versus external factors was investigated. When setting guidelines, however, it was decided that those missions that had extreme growth, as defined by missions that had greater than a 40% cost growth, would be excluded from consideration. Based on the previous discussions, it was assumed that missions with greater than a 40% cost growth had unrealistic or overly aggressive assumptions that led to this excessive growth and should not be used in setting guidelines for missions that are initially properly scoped. It should be noted that a large number of non-restricted missions, 14 out of the 32, fell into this category.

Table 2 explains the basis for these recommendations from the resulting data set of 18 non-restricted missions. To provide the basis, the 18 missions were segmented into two groups: the 13 missions that experienced internal factors for growth, and the 5 missions that experienced external factors for growth. Assuming this mission data set is representative of any typical mission data set, these percentages 72.2% and 27.8%, respectively, were used to set the percent likelihood or probability that a mission would experience internal versus an external growth. This percent likelihood is then multiplied by the average cost and schedule growth to provide the basis for the recommendations. The average cost and schedule growth numbers reflect the averages across the mission data set of 13 and 5 mission data, respectively, determined for the internal versus external growth categories. An expected cost growth number was then calculated based on the multiplication of the percent likelihood that a mission would experience growth times the average growth. The expected schedule growth numbers were calculated for each segment in the same manner as the cost.

Table 2: Summary of Expected Schedule and Cost Growth Results

Reason for Growth	Percent of Total Missions	Average Historical Cost Growth (%)	Average Historical Schedule Growth (%)	**Expected Cost Growth (%)**	**Expected Schedule Growth (%)**
Internal	72.2%	15.0%	15.6%	**11%**	**11%**
External	27.8%	9.8%	18.4%	**3%**	**5%**

Figure 16 provides a summary of the total reserves that are suggested based on the historical data and represents the cost and schedule reserve roll-up, and what level of reserves are to be considered for control at the Project versus Program level. As will be described in the following paragraphs, the total reserve suggested for cost is on the order of 33% where 19% is held by the Project, as it has been demonstrated that properly scoped project can successfully manage cost and schedule with that level of reserve, while another 14% is held at the Directorate or Program level to cover extraordinary problems arising from internal factors as well as external delays outside of the project's control. The combination of these numbers totaling the 14% suggested is shown in Table 2 in the column entitled "Expected Cost Growth".

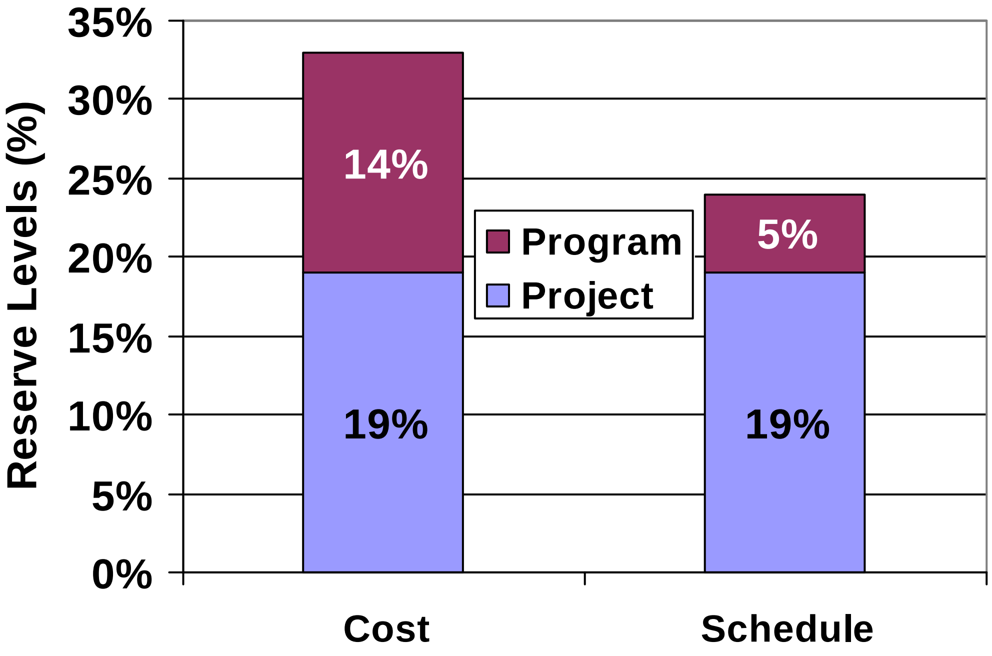


Figure 16: Suggested Reserve Levels

Additionally, schedule reserves should be set at 24%, where an additional 11%, as shown in Table 2, or 6 weeks per year of development, should be held at the Project level over and above the 8%, or 4 weeks per year of development typically held by Projects, while another 5%, also shown in Table 2, or 2.5 weeks per year of development, should be funded at the Directorate or Program level to cover external growth outside of the project's control. Specific recommendations and rationale follow.

Require better technical and programmatic definition at the beginning of a project

An examination of this historical data set suggests that many NASA projects may have underestimated the requirements and other internal technical and programmatic factors under the project's control, which drive cost and schedule for their projects. NASA should consider 1) requiring new projects to show in detail the historical data upon which they are basing their technical, programmatic, and cost and schedule estimates, and 2) attempting to obtain outside disinterested third party estimates of the technical and programmatic requirements, i.e. a notional mission design, and then base project funding on these requirements and historical cost data. These detailed bases of estimate should be provided for the technical, programmatic and cost components.

The additional effort required for a more robust initial estimate has been recognized in the Discovery Acquisition process as the Phase A Concept Study Report effort for the latest Discovery AO has been increased to $1.2M over a 7-month study versus $450K over a 4-month study in the last Discovery AO that resulted in a Step 2 selection.[19,20] Even given inflation, this represents a doubling of the effort expended to increase the fidelity of the definition of the initial mission concept.

Early Instrument Development to Reduce Risk

As shown previously in Figure 4, instrument development problems were the primary cause of internal growth. Additionally, Figure 13 showed that instrument development problems led to significantly greater cost growth than spacecraft development problems. The discussion in section 4.3 postulates that a phased development approach, where instrument development is initiated prior to the start of spacecraft development, could lead to the reduction of unplanned marching army costs that could be avoided when the instrument development problems delay spacecraft development integration and test activities. It is suggested that a key possibility for limiting total cost growth is developing the instrument earlier. Based on this hypothesis, it is recommended that earlier instrument development, such as having the instrument Critical Design Review (CDR) prior to the spacecraft and mission Preliminary Design Review (PDR). In this way, the majority of instrument risk will be removed or identified prior to spacecraft development such that additional delays can be avoided or managed such as not to impact the spacecraft development.

Increase cost reserves

As shown in Table 2, the expected cost growth over and above reserves is 11% for internal growth, and 3% for external growth, for a total of 14% growth. A closer evaluation of project data and requiring better initial technical and programmatic data for new projects may reduce some of this cost overrun due to internal technical growth, but the amount, at this point, is unknown.

The authors suggest that NASA consider pursuing the ability to maintain reserves either at the Directorate or Program level (outside the control of the Project) to cover the expected cost growth of 14% due to both internal and external growth factors. This cost reserve would be over and above the 19% cost reserves that has typically been held at the Project level.

The 19% number suggested to be held for the projects is based upon the evidence that some restricted missions, which have been properly scoped, have been successfully managed by their projects with this level of reserve. This reserve amount carried by the project should cover all "known unknowns", in which a risk is known but the cost and schedule impact is not fully understood or characterized, as well as a large percentage of the "unknown unknowns", in which a risk item has not yet been anticipated by the project.

Over and above these Project reserves of 19%, 14% reserves to be maintained at the Directorate or Program level (outside the control of the Project) should be considered to cover unknown unknowns that are outside the range of typical problems that may occur. Examples of these extraordinary problems are the problems with the High Voltage Power Supply on Cloudsat and the industry wide processor problems that affected several projects during the last few years. This residual reserve would be carried by the Program to cover for the *extraordinary* internal growth factors; however, the criteria by which the Project may be granted these funds from the Program should be stringent.

Increase funded schedule reserves

As shown in Table 2, the expected schedule growth over and above reserves is 11% for internal growth, and 5% for external growth. The Projects have traditionally held 1 month per year of development, or 8% reserves.

Based on these data, the required project schedule reserves should be increased to 19%, or 10 weeks per year of development, for a start as both restricted and non-restricted missions have schedule pressure with the current industry guidelines of 1 or 1.8 months per year of development.[21] This 19% schedule reserve to be held at the Project level represents an increase from the 8%, which is the more typical reserve level held.

The authors would further suggest considering the ability to maintain additional reserves either at the Directorate or Program level to cover the expected 5% schedule growth due to external factors. At the Program level, this schedule reserve translates into holding funded cost for another 2.5 weeks per year of development, at the peak burn rates.

6.2 Comparison to Industry Guidelines and Rules of Thumb

Table 3 and 4 represent the suggested cost and schedule reserves, respectively, from a variety of different industry sources. Notice that these guidelines, which are roughly 25% for cost and 15% for schedule, are consistent with the project-level reserves recommended above but are not sufficient to cover all potential growth. As stated previously, developing a more robust initial concept and cost and schedule estimate should decrease the amount of growth; moreover, the additional reserves suggested, to be held at the Directorate or Program level, should provide a higher probability that projects can come in on cost and on schedule.

Table 3: Summary of Aerospace Industry Cost Reserve Guidelines

Value	Source	Comment
25-35%	NASA Mission Design Process[22]	Based on Pre-Phase A suggested Cost reserve
30%	JPL Design Principles[23]	Value at proposal stage
10-50%	Johnson Space Center (JSC) Guidelines[24]	Based on design maturity relative to "State of the Art"
25%	NASA AO Cost Reserve Guidelines[25]	Required Phase C/D development cost not including launch cost
30%	NASA LaRC Guidelines[26]	Budget reserve required at PDR based on project experience
20-25%	Department of Defense[27]	Result of most probable cost analysis

Table 4: Summary of Aerospace Industry Schedule Reserve Guidelines

Value	Source	Comment
8%	Industry "Rule of Thumb"	Equates to 1 month per year of development
15%	NASA Mission Design Process[28]	Equates to 1.8 month per year of development
15%	JPL Design Principles[29]	Based on JPL guidelines for an assumed four year development

6.3 Best Practices for the Control of Cost and Schedule

As part of the research for this paper, a series of lessons learned or best practices were identified from the papers of some of the missions. These best practices are summarized below.

Proper Mission Scoping
A paper authored by Tony Spear on lessons learned on the Mars Pathfinder mission stated: "Fundamental to our approach was starting the project with an adequate pot of $ reserves: This we did by carefully

scoping the Mission properly at the outset. We could have flown more Science, for instance, or more redundancy. We looked at flying a Seismometer and instruments to detect Hydrogen and soil toxicity, but backed off."[30] The Advanced Composition Explorer (ACE), which was one of the few missions that returned funding to NASA, stated in a lessons learned report: "Drawing a tight constraints box around a developer while withholding the wherewithal to help him solve his problem will only cause him to dissipate excessive resources working against one brick wall (e.g., mass reduction), while sacrificing another (e.g., schedule)."[31] These comments about proper mission scoping are directly counter to the substantial optimism that led to the cancellation of the FAME and VCL missions as noted earlier.[14,15]

Robust Initial Cost and Schedule Estimates

As stated in a paper describing the cost approach of the Applied Physics Laboratory at John Hopkins University (JHU/APL) which managed two projects, NEAR and ACE, that returned funding to NASA: "The ability to generate accurate program cost estimates and control these costs through program completion has become an important attribute to JHU/APL over the years".[32]

Monthly Estimates to Complete

Pathfinder also assessed the status of resources to go and the reserves held against them on a monthly basis. As stated in the Pathfinder lessons learned document: "Each month, all elements of the Project Team got together to assess fiscal, technical and schedule performance. We then allocated some of our $ and schedule reserves as needed, revising our 'Estimates to Complete'. If necessary, we re-planned an activity if it exceeded its target completion cost-- either by descoping it or allocating additional $ to it from reserves. We then added up these individual estimates to derive the total Project Cost to Complete estimate."[33]

Importance of Managing to Schedule

In a presentation describing lessons learned on managing the IMAGE mission, which had limited cost and schedule growth even though it was a non-restricted mission, Dr. Jim Burch and Mr. Bill Gibson stated: "The IMAGE team believed that if we missed our launch date, the mission would be cancelled" and "Critical to overall project success, cost cannot be controlled if the schedule is not controlled."[34] This is also proven out by the lower average cost growth of restricted missions (4.5%) vs. non-restricted missions (32.6%) as shown previously in Figure 9.

Effective Use of Earned Value Management (EVM)

Both the IMAGE and Stardust missions used EVM as an early warning device to identify potential cost and schedule issues. As stated for the IMAGE mission: "The Earned Value system worked well as an early indicator of cost problems ahead"[35] while, for Stardust: "In sum, the integrated earned value approach of the STARDUST program has proven itself many times to provide substantiated early-warning to problems, thus facilitating timely application of resources to recover."[36]

Application of these best practices from lessons learned from missions that experienced limited cost and schedule growth, should lead to reduced cost and schedule growth when applied to future missions.

7 Summary

This paper investigated recent NASA cost and schedule growth history for forty science missions. These missions included both Space and Earth Science missions and covered Programs, such as Mars Surveyor and Exploration, Discovery, Medium and Small Explorer (MIDEX/SMEX), Earth System Science Pathfinder (ESSP), New Millennium and others.

An examination of this historical data set has shown that the majority of projects had experienced cost and schedule growth (87.5%), and that this cost and schedule growth is substantial. The average cost and schedule growth for the mission set is 27% and 21.5%, respectively. The data also illustrated that cost and schedule growth are correlated; a general rule of thumb could be followed that states that for every percent of schedule growth, there will more than likely be an equal or greater percent of cost growth.

Moreover, the data highlighted that the primary internal reason for cost and schedule growth is instrument development issues, and the fundamental external reason for the growth is launch vehicle delay. It is also more likely that a project will have experienced internal reasons for the cost and schedule growth versus external reasons.

The paper discusses reserve guidelines, and finally concludes with a number of recommendations that suggest that better technical and programmatic definitions at the beginning of a project are needed as well as a potential movement of a large portion of instrument development, prior to the start of spacecraft development, in order to avoid overall system cost growth. Relative to reserve recommendations, it is suggested that an increase in cost and schedule reserves for projects, some to be held outside the project, may need to be considered by NASA. In addition, lessons learned from missions that experienced limited cost and schedule growth, such as proper mission scoping, robust and realistic initial estimates, assessment of monthly estimates to complete, managing to schedule and the effective use of EVM, should be applied to future missions to control cost and schedule growth.

8 About the Authors

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