Space Chicken: A Historical Look at How the Critical Path Changes over a Mission's Development

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Abstract*—*The critical path in schedule analysis defines the series of tasks that have no schedule slack leading to the delivery of a system. The critical path for NASA science missions, which typically runs through a spacecraft subsystem or a scientific instrument, is dynamic and changes over the development lifetime of a project. Often the critical path at the start of preliminary design will be through a specific spacecraft subsystem while the final, delivered critical path item is often a scientific instrument that is delivered late. The research for this paper looks at the postulated critical path at different milestones, and the actual critical path item at final delivery, for a variety of NASA science missions to understand what elements are impacting the delivery schedule the most. Recommendations are made based on these quantitative results relative to what elements should potentially be considered more often in early development schedules to more robustly plan for development issues.

TABLE OF CONTENTS

1. INTRODUCTION

The critical path of a project is defined in the NASA Systems Engineering Handbook [1] as "the sequence of dependent tasks that determines the longest duration of time needed to complete the project." Assessing the critical path of a NASA science mission requires a keen understanding of the development challenges that are inherent in meeting mission requirements. These challenges arise from many sources including technology development required for the mission, the development and/or manufacturing of spacecraft and/or instrument hardware, or the integration of the spacecraft and/or instrument(s) and/or activities required to integrate and test the complete satellite. Identifying the critical path is based on recognizing these potential challenges as well as the previous experiences of the project team and their biases.

The critical path of the project is dynamic, changing as the project evolves. As the NASA Systems Engineering Handbook [1] states, "As the project progresses, the critical path will change as the critical tasks are completed or as other tasks are delayed." The determination of what element should be on the critical path during the mission is often subjective, since it is a forward forecasting schedule, and requires the full insight and recognition of the project team. For example, if a spacecraft subsystem is on the current critical path, but an instrument is 3 days off the critical path and has just suffered a setback, the instrument lead may not immediately volunteer that their instrument should be placed on the critical path. The instrument lead may have mitigation strategies to investigate, and may want to wait to see if the spacecraft or other elements could suffer delays that would keep their instrument off the critical path. This is often referred to in the space industry as "space chicken" where some element leads that are close to, but not on, the critical path may not disclose how close they are to the critical path while assuming that some other element will experience a delay. The term "space chicken" is derived from the term "playing chicken" which is defined [2] as "to engage in a test of courage in which, typically, two vehicles are driven directly toward one another in order to see which driver will swerve away first."

For NASA science mission developments, the selection of the critical path is typically a choice between the spacecraft bus, and its subsystems, and the scientific instrument(s). As the Aerospace industry has developed over time, spacecraft busses have become more common to be more of a commodity item with "standardized" busses. NASA science instruments, however, which constantly push the state of the art to achieve world-class science, are typically more of a development challenge. As noted by the NASA Office of the Chief Engineer, instrument development can become the primary technological challenge for the success of a mission [3]. The difficulty of developing a world-class instrument can lead to delays in its delivery to the spacecraft for system integration and test (I&T) [4]. These delays can lead to cost growth while the spacecraft, mission, and ground system team waits for the instrument to be delivered. The subsequent "marching army" cost can be significant and is one of the primary causes of cost growth for NASA missions [5].

The difficulty of instrument development versus spacecraft development can be seen when investigating resource growth for historical NASA missions. A previous study reviewing a subset of 20 NASA missions in greater detail demonstrated

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that resources such as mass and cost grew at a significantly greater rate for instruments than spacecraft [6]. Figure 1 shows the average percentage mass and cost growth of the instruments and spacecraft from the start of Phase B for the 20 missions in the previous study and shows that the growth for instruments is essentially twice the growth for spacecraft. This incongruity implies that instruments typically are less mature or experience more volatility than spacecraft at the initiation of a project, as shown by the differences in mass growth, and implies that this lack of maturity can lead to higher cost growth for the instrument relative to the spacecraft.

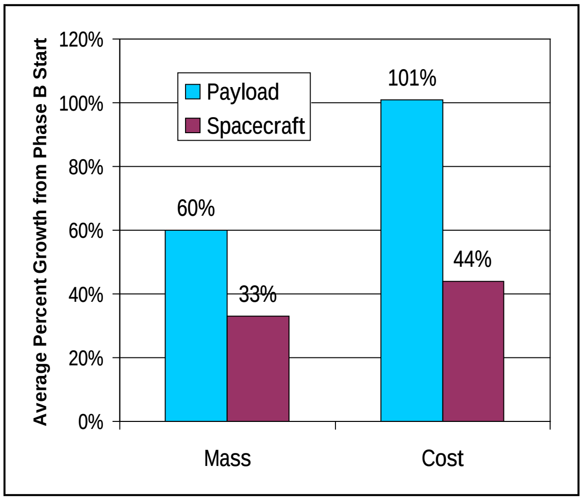

Figure 1. Mass and Cost Growth, from Phase B Start, of Instrument Payloads vs. Spacecraft [6]

Instrument immaturity can lead to development issues which lead to schedule growth. A previous instrument schedule growth study conducted for 86 NASA instruments showed an average schedule growth of 10.4 months, or 32.3%, from Phase B start to delivery [4]. Figure 2 shows the plot of planned versus actual instrument delivery durations which indicates that almost all were delivered late.

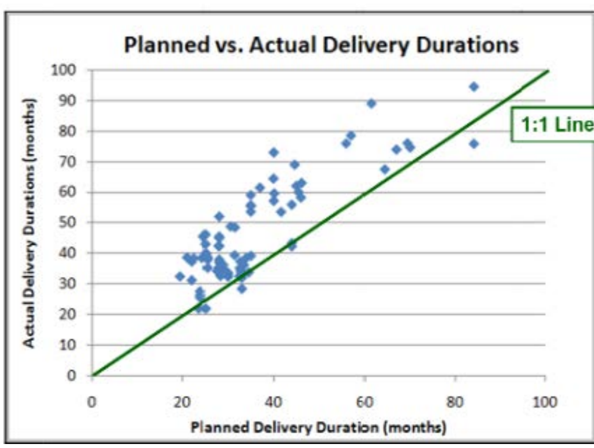

Figure 2. Comparison of Average Actual vs. Planned Durations of 86 NASA Instrument [4]

The previous study [4] also looked at what phase the schedule growth occurred and identified that, although the growth began after the Preliminary Design Review (PDR), the majority of schedule growth happened after the Critical Design Review (CDR). Figure 3 shows the average growth relative to milestones and shows that a growth of 7.5 months, or 49.7% over the planned duration, occurred from CDR to delivery.

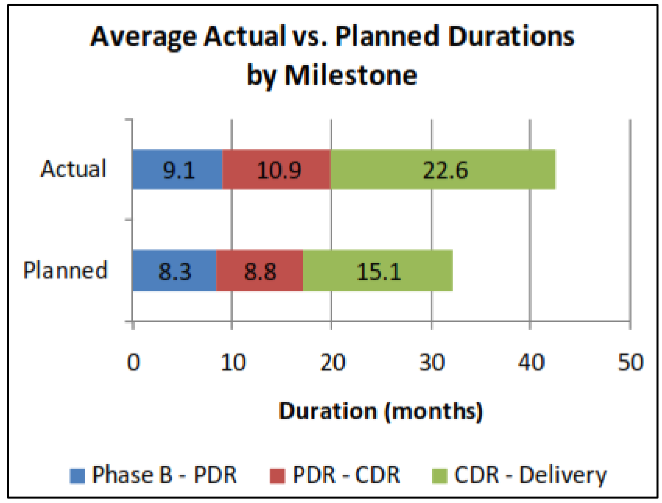

Figure 3. Comparison of Average Actual vs. Planned Instrument Development Phase Durations [4]

The NASA Space Flight Program and Project Management Handbook also identifies that the instrument development schedule growth is significant stating that "recent analysis of instruments developed between August 1990 and November 2009 shows the average instrument development schedule growth was 33 percent or about 10 months" which is consistent with analysis presented in this paper and the previous studies [7].

More recent studies have looked at the resource growth for 80 NASA instruments and 46 NASA spacecraft [8], [9]. The studies, which looked at the growth of mass, power, cost, and schedule at different milestones, showed that instrument growth, in all cases, was significantly higher than spacecraft growth. Specifically, the average schedule growth for NASA instruments from the start of Phase B was 36%, while the average schedule growth for NASA spacecraft was 28% [8], [9]. The data from these studies demonstrates that science instruments have more difficulties in development than NASA spacecraft.

2. STUDY APPROACH

To identify the historical critical paths for NASA missions, schedule data was collected for 40 different missions at different milestones, as shown in Table 1. Schedules for each milestone were collected to determine if the instrument or the spacecraft were on the critical path. Milestones included the start of Phase B, otherwise known as Key Decision Point B (KPD-B), PDR, CDR, and at final delivery.

Table 1. List of Missions Included in Study

Mission	Science Type	Launch Year
TRMM	Earth Science	1997
Terra	Earth Science	1999
RHESSI	Heliophysics	2002
ICESat	Earth Science	2003
GALEX	Astrophysics	2003
Spitzer	Astrophysics	2003
SWIFT	Astrophysics	2004
Deep Impact	Planetary	2005
MRO	Planetary	2005
New Horizons	Planetary	2006
CloudSat	Earth Science	2006
STEREO	Heliophysics	2006
THEMIS	Heliophysics	2007
AIM	Heliophysics	2007
Phoenix	Planetary	2007
DAWN	Planetary	2007
Fermi	Astrophysics	2008
IBEX	Heliophysics	2008
OCO	Earth Science	2013
Kepler	Astrophysics	2009
LRO	Planetary	2009
WISE	Astrophysics	2009
SDO	Heliophysics	2010
Juno	Planetary	2011
NuSTAR	Astrophysics	2012
RBSP	Heliophysics	2012
LDCM	Earth Science	2013
IRIS	Heliophysics	2013
LADEE	Planetary	2013
MAVEN	Planetary	2013
GPM	Earth Science	2014
SMAP	Earth Science	2014
MMS	Heliophysics	2015
OSIRIS-REx	Planetary	2016
CYGNSS	Earth Science	2016
TESS	Astrophysics	2018
InSight	Planetary	2018
Parker Solar Probe	Heliophysics	2018
ICESat-2	Earth Science	2018
ICON	Heliophysics	2019

The missions include schedule data collected from 8 Astrophysics, 11 Heliophysics, 10 Earth Science, and 11 Planetary Science missions as identified in Table 1. The data set includes 15 missions managed by the Jet Propulsion Laboratory (JPL), 15 by the Goddard Space Flight Center (GSFC), and 10 by other organizations. The missions provide a robust representation of different NASA mission types, organizations, and science objectives.

For the 40 missions shown in Table 1, the critical path was assessed based on the mission's project schedule at each major milestone. The dates were recorded for the spacecraft and instrument(s) delivery to system I&T and the critical path was assessed. In most cases the critical path was clearly defined but, in some cases, typically early in a project's lifecycle, multiple elements may have all been on the critical path to be delivered into system I&T at the same time. In those cases, it is noted that both the spacecraft and instrument(s) are on the critical path.

3. Historical Critical Path Results

The importance of properly identifying the critical path cannot be overstated. If the critical path is improperly determined early in the project, then the project can be delayed and incur a "marching army" cost awaiting the delivery of the critical component on the true critical path. This effect is notionally illustrated in Figure 4 where the development duration of the instrument was understated such that the instrument delivery is delayed resulting in the start of the system I&T phase being delayed. In the example, the project would incur a marching army cost awaiting the instrument delivery.

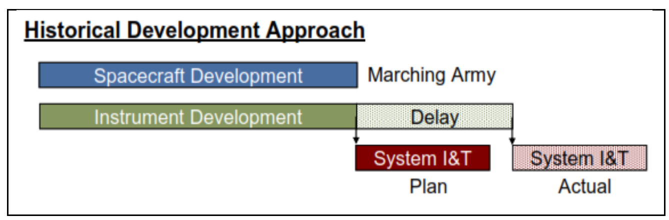

Figure 4. Instrument Delay Effect on Project Schedule

The impact of marching army cost can be significant. A previous study [10] investigated the contribution of schedule delay to "marching army" cost and determined that "21 of the 28 missions (75%) have estimated cost growth due to schedule growth greater than 50% while the average contribution of estimated cost growth due to schedule growth for the complete mission set was 73%, indicating that schedule growth can be a significant contributor to cost growth."

The results of the analysis from investigating the 40 missions listed in Table 1 are shown in Figure 5, which identifies the percent of the time at each milestone the spacecraft or the instrument was on the critical path. As can be seen for KDP-B at PDR and at CDR, the percentage of time the spacecraft and instrument are on the critical path is essentially equivalent. This implies that the project team considered either element to be as likely on the critical path with the instrument being identified approximately half the time and the spacecraft identified the other half. At delivery, however, the percentage of time that the instrument is on the critical path is greater than 3 times more likely than the spacecraft, with the instrument being on the critical path 77.5% of the time while the spacecraft being on the critical path 22.5% of the time.

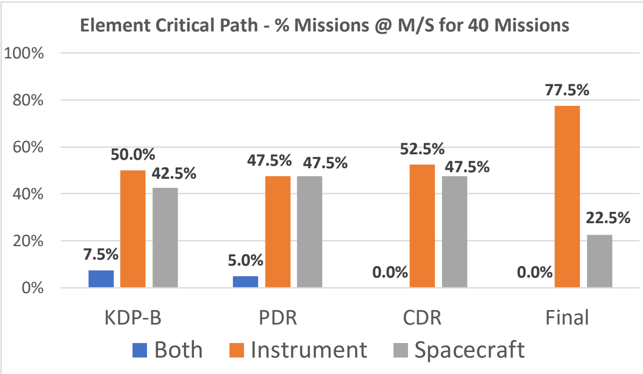

Figure 5. Critical Path Summary at Each Milestone

To dive further into the data, the schedule growth from Phase B to delivery for both the instrument and the spacecraft, which compares the initial planned delivery duration at the start of Phase B to the final actual schedule duration at delivery, was calculated for each mission. The average schedule growth for the instrument is 33.8% and the spacecraft average schedule growth is 25.3%, which is consistent with the 38% and 26%, respectively, from previous studies [8], [9]. This equates to an average schedule delay of the instrument being 14.2 months while the average spacecraft delay is 9.5 months, a difference of over 4 more months for instruments compared to spacecraft. Due to the "space chicken" effect, however, the real difference between instrument and spacecraft development duration may be greater.

The difference between different science types was also investigated with both Earth Science and Astrophysics having the longest average instrument delays at 19.4 and 18.2 months, respectively. This is intuitive given that Earth Science and Astrophysics instruments are typically more complex than Planetary and Heliophysics instruments. The difference between instrument and spacecraft delays was consistent, however, with the range being from 3.5 months for Planetary science missions to 6.1 months for Earth Science missions. In addition, the spacecraft was on the critical path at delivery roughly a similar percentage of the time with the low range being Heliophysics at 18.5% and the high range being Planetary at 27.3% of the time.

In addition, the majority of growth in planned versus actual instrument delivery duration occurs after CDR. Of the average 33.8% growth that occurs from Phase B to instrument delivery, two-thirds of that growth occurs after CDR. The average planned duration from CDR to instrument delivery for the missions studied was 15.9 months whereas the actual duration was 24.9 months, an increase of 9 months or 56.5% great than planned. These results are consistent with the values shown in Figure 3 from a previous study, and indicate that most of the instrument schedule growth is not identified until after CDR.

4. RECOMMENDATIONS

The clear indication that over 75% of the time the instrument will be on the critical path should solicit recommendations that projects set the critical path going through the instrument(s) throughout their lifecycle. These recommendations come in the following form:

1) Increased awareness of instrument critical path tendencies
2) Increased instrument schedule reserves
3) Better assessment of instrument schedule duration
4) Change in acquisition approach

Each of these recommendations are discussed in the following sections.

4.1 Increased Awareness of Instrument Critical Path Tendencies

One of the primary, obvious questions that arise is, how can spacecraft be forecasted to be on the critical path at KDP-B, PDR, and CDR greater than 25% of the time when more than 75% of the time, the instrument finished on the critical path? Increasing the awareness of instrument schedule growth, such as this paper, previous studies, and NASA's own analysis, is important in helping NASA projects to consider the instrument as the primary critical path more often. An approach that could be considered is to document that the instrument should be the primary consideration for the critical path when developing an initial schedule. The authors reviewed the NASA Systems Engineering Handbook, the Expanded Guidance for NASA Systems Engineering Volume 1, and the NASA Schedule Management Handbook and, although all address how to determine the critical path in NASA projects, none identified the instrument(s) as the primary critical path hardware item to be considered [1], [11]–[12]. A simple section emphasizing the instrument early on the critical path and including historical data, similar to references [4], [7]–[8], and the results of this paper, could potentially influence project managers (PM) to consider the instrument as the critical development item.

The authors also postulate that there is an unintentional bias against putting the instrument initially on the critical path due to the majority of PMs who come from a spacecraft system engineering or spacecraft-subsystem background such that their main development concern is the spacecraft. A quick look at the background of the PMs for the last 10 missions included in the analysis identify that 7 of the PMs have primarily a spacecraft development background. The background of the PMs could bias the early critical path selection from a spacecraft perspective as opposed to looking more closely at the instrument.

In addition, merge bias may be a consideration for the spacecraft. Merge bias is defined as the impact of having two or more parallel paths of activities, each with its own variability or uncertainty, merging into one milestone or other activity [13]. The sheer number of components for a spacecraft may lead to a bias toward placing the spacecraft on the critical path given that there are more spacecraft schedule tasks specified early in a project's life than instrument tasks as the project schedule is initiated. It is suggested that the project planning and control process would benefit from additional insight into merge bias and perhaps be aware of the number of tasks associated with the spacecraft and instruments at a project's initiation to ensure limited bias.

4.2 Increased Instrument Schedule Reserves

Previous studies have identified that industry standard schedule reserve guidelines are focused more at the system level and typically underestimate the amount of reserve required based on historical data [8]. For example, GSFC's GPR 7120.7 equates to roughly a 13% schedule reserve from the start of Phase B for a typical 6-year development while JPL's Design Principles also equates to roughly 10% schedule reserve for the same duration [14]–[15]. These reserves, however, are significantly lower than the historical 33% or greater instrument schedule growth than has been shown in both references [7]–[8], and this study. The 33% equates to a rule of thumb of 4 months of reserve out of every year of development, which is considered to be excessive given the general rule of thumb of 1 to 2 months out of every year of mission development. The authors believe that it would be much better to more accurately forecast the duration of instrument schedules, as discussed in Section 4.3, than to supply such a large amount of allocated reserves. Some lengthening of schedule reserve, however, is a worthwhile consideration for instruments specifically.

4.3 *Better Assessment of Instrument Schedule Duration*

One way to determine the critical path early in a project's lifetime is to use historical data to estimate the development duration of both the spacecraft and instrument(s). Aerospace began collecting schedule data for both complete mission development durations, spacecraft and instrument development durations, and satellite I&T durations in the early 2000s. Collection of this data led to the development of a schedule estimating tool where specific analogies are used to estimate development durations of the spacecraft and instrument to determine which may be on the critical path [16]. This tool is used by Aerospace to provide feedback on a project's development schedule to provide recommendations on making the schedule more robust.

NASA has also put forth a major effort to collect schedule data in the Cost Analysis Data Requirement (CADRe) activity that is essential in helping assess reasonable cost and schedules [17]. The NASA Instrument Cost Model (NICM) utilizes CADRe data, and other sources, to also provide insight into the potential instrument development duration [18].

4.4 Change in Acquisition Approach

Changing the acquisition approach may also provide some relief in developing a more realistic critical path early in the project lifetime. A potential alternative acquisition approach, presented previously by one of the authors and the NASA Earth Science Technology Office, is to start the instrument development prior to mission start, otherwise known as an instrument first, spacecraft second (IFSS) approach [19]. The IFSS approach brings the instrument(s) to a CDR level of maturity prior to starting a mission which, by design, places the instrument on the critical path from the beginning. The IFSS approach has been identified to significantly reduce the collateral mission cost growth due to instrument delays and result in more missions being funded for less cost when utilized for a portfolio of missions [20].

5. SUMMARY

This study provides a historical assessment of the critical path for 40 NASA science missions. The results show that instrument development duration growth is greater than spacecraft development growth. Further, the instrument is on the critical path prior to System I&T more than 75% of the time even though the instrument and spacecraft are equally specified as the critical path at early project milestones. This implies a need to increase consideration of putting the instrument on the critical path early in the project's development. Recommendations include increasing the awareness of instrument development difficulties by publicizing supporting research and codifying in NASA handbooks, potentially increasing schedule reserves dedicated to instruments, using historical data to more accurately estimate instrument schedule durations, and potentially following an IFSS acquisition approach to minimize the impact of instrument delivery schedule delays on mission development. More accurately forecasting the instrument development durations and placing the instrument on the critical path early in a project's lifecycle, will allow for a more robust schedule to minimize both overall mission schedule and cost growth.

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BIOGRAPHY

Robert Bitten *is a Technical Fellow at The Aerospace Corporation and has conducted independent cost estimates for NASA proposal evaluations and independent assessments for a variety of different NASA missions and organizations. He is a winner of The Aerospace Corporation's President's Award for his effort in assessing the cost effectiveness of different alternatives in the Hubble Space Telescope Remote Servicing Module Analysis of Alternatives. He also won the 2007 NASA Cost Estimating Support Contractor of the Year Award that is awarded to recognize an individual who has provided "outstanding contractor support to the NASA cost estimating community and significantly contributed to the field of cost estimating." He has a Bachelor's in Industrial and Systems Engineering (B.I.E) from the Georgia Institute of Technology and a M.B.A. from Pepperdine University.*

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