Conference Paper

Lessons Learned from New Subsystem Development in Manned Space

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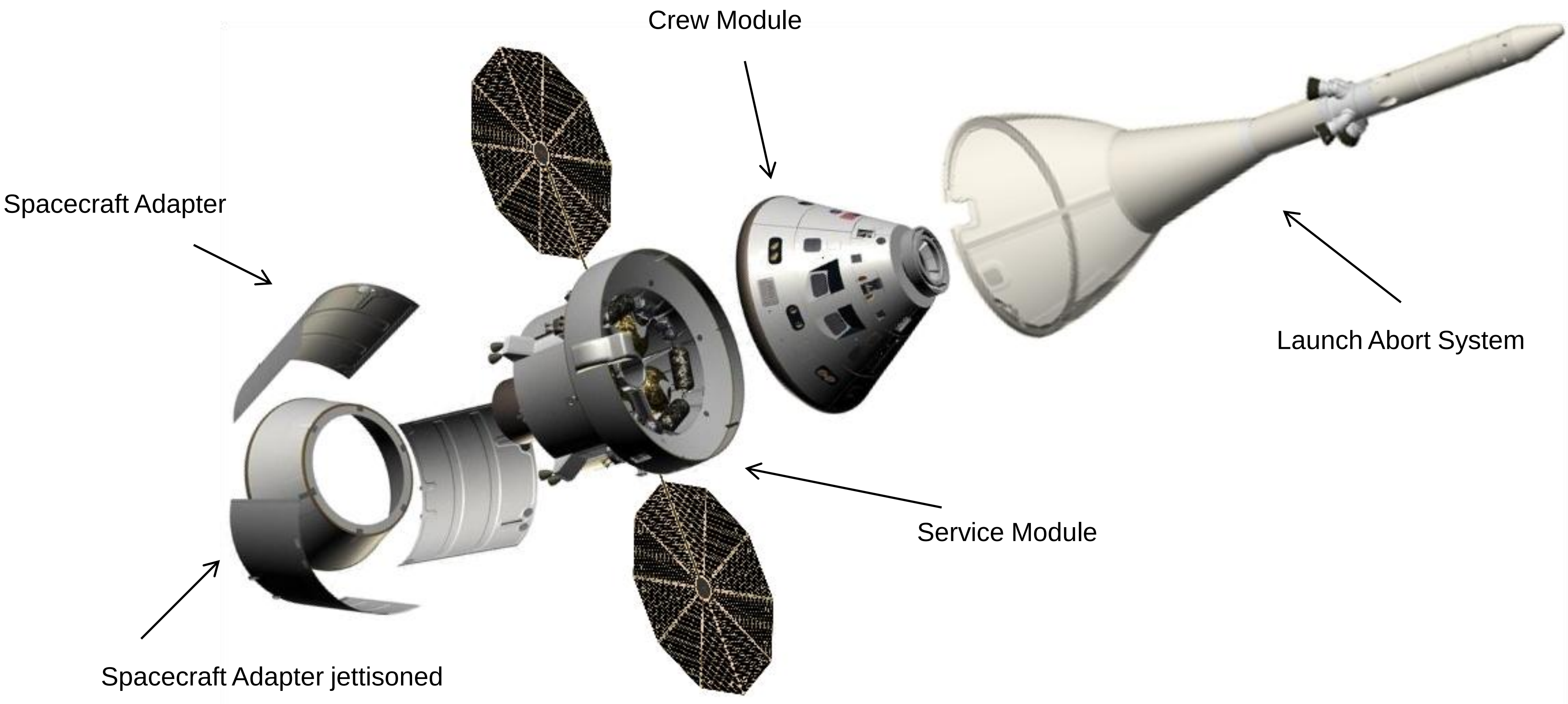
Our objective is to relate some lessons learned about modeling schedule uncertainty from a project to develop a rocket system

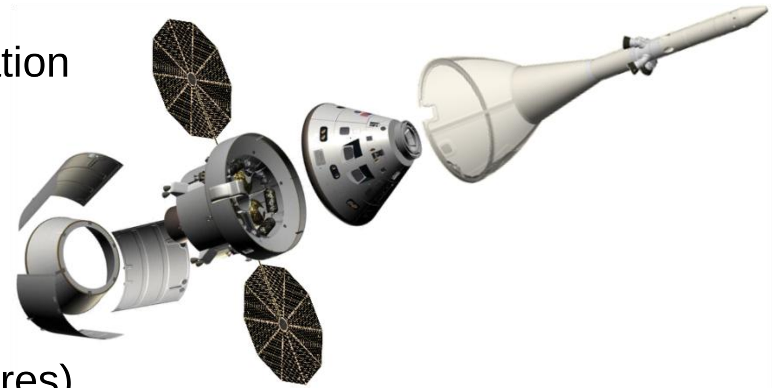
- Overview of the rocket system
- Original expectation the project had for schedule and cost
- Actual outcome to date for schedule and cost
- Explanation for cost over run and schedule slips
- Examination of methodology for addressing cost and schedule risks

The development system we will draw our example from is NASA's Crew Exploration Vehicle or Project Orion



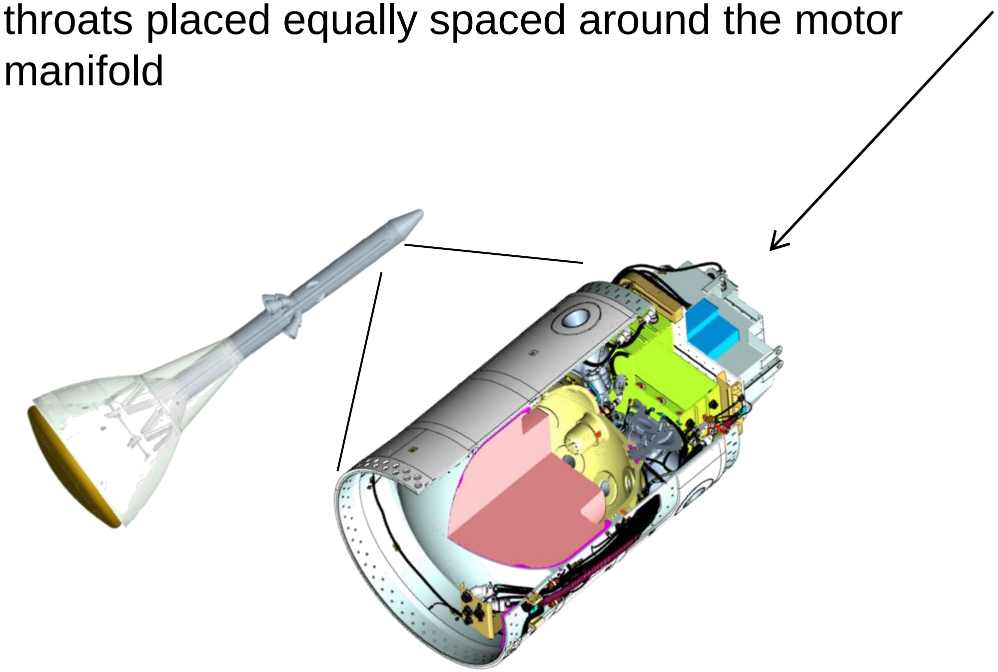
The development of the CEV is composed of many subsystems all of which face DDT&E challenges

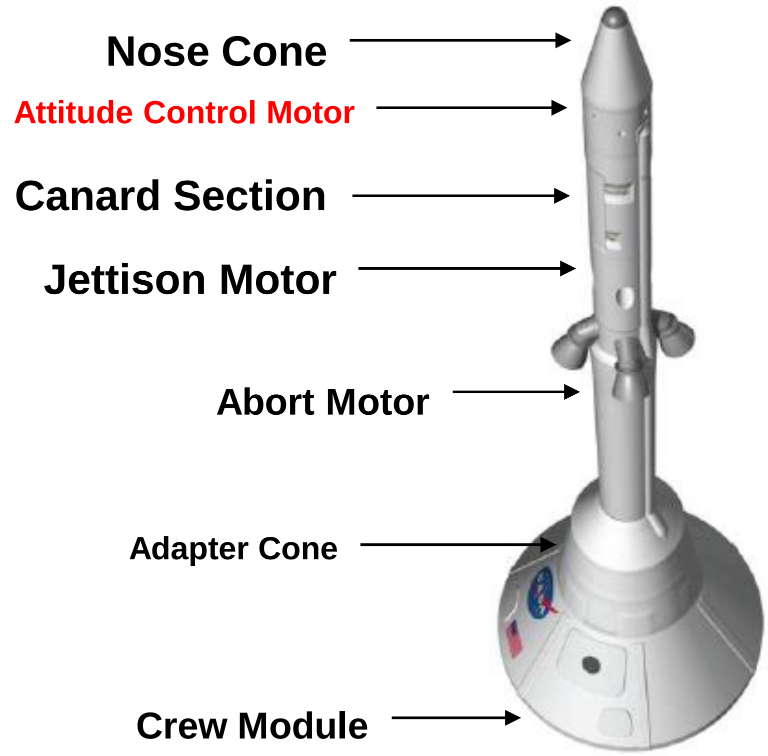
- Launch Abort System has three motors
  - Motor development
- Crew Module has Environmental Control and Life Support Systems
  - Electrical, Electronic, and Electromechanical part radiation testing
- Service Module has propulsion
  - Main engine development
- Spacecraft Adapter to mate with Crew Launch Vehicle (Ares)
  - Mass constraints



We will examine the effect the Attitude Control Motor (ACM) had on Launch Abort System (LAS) development

- A complex integration of solid fuel pressurized volume that produces thrust anywhere in a planar vector by computer firmware controlled mechanisms that drive a pintle valve in-and-out of eight nozzle throats placed equally spaced around the motor manifold





As with any DDT&E program a test plan is the necessary means of assessing that a design successfully meets requirements

- The goal of the development plan was to raise the TRL of the various components of the LAS to a TRL of 6 prior to Qualification Testing
  - System/subsystem model or prototype demonstration in a relevant environment

Initial Orion Flight Test Plan

Activities	Government Fiscal Year					
	2009	2010	2011	2012	2013	2014
Pad Abort 1 (PA-1) Ascent Abort 1 (AA-1)	11/2008 5/2009					
Pad Abort 2 (PA-2) Ascent Abort 2 (AA-2)		5/2010 8/2010				
Ascent Abort 3 (AA-3) Ascent Abort 4 (AA-4)			2/2011 9/2011			
Orion 3					9/2013	
Orion 4 Initial Operational Capability (IOC) Orion 5						6/2014 9/2014

And the overall test plan must rely upon a test plan of the component of the overall system

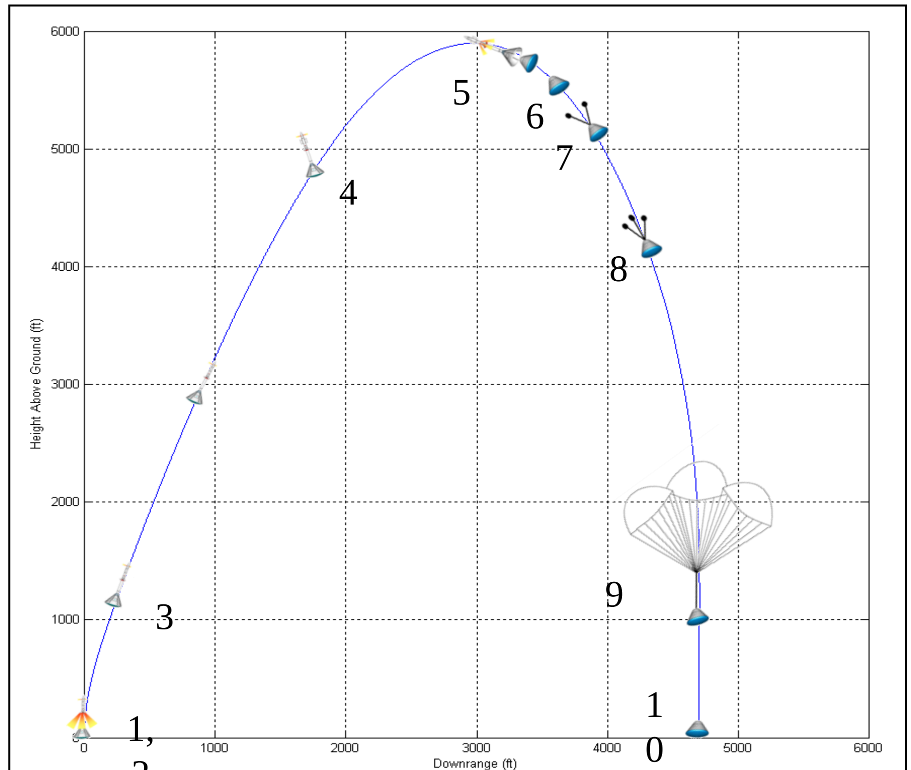
Initial ACM development test plan

Activities	Month / Year													
	10/07	11/07	12/07	1/08	2/08	3/08	4/08	5/08	6/08	7/08	8/08	9/08	10/08	11/08
ACM High Thrust test (HT-4) ACM HT-5	▲	▲												
ACM HT-6 ACM HT-7		▲ ▲												
ACM full scale OAT-3						▲								
Development Motor (DM-1) full scale						▲								
Pad Abort 1 (PA-1)														▲

A lot of attention was focused on the Pad Abort 1 test as it was the first visible demonstration of Orion vehicle development

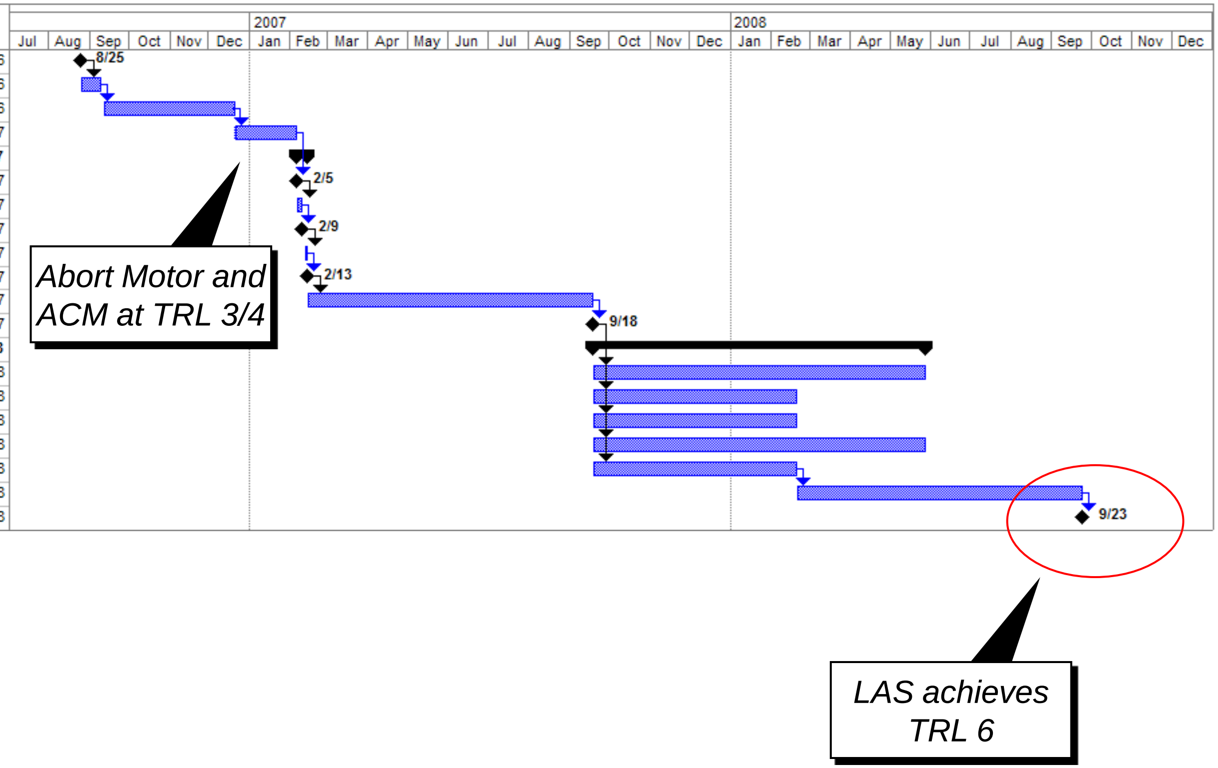
- The flight test demonstrates the capability of the LAS to propel the module to a safe distance from the launch vehicle and the performance of the abort, jettison and attitude control motors

Event	Time Since Ignition (seconds)	Event
1	0.00	Ignition of abort and pitch motors
2	0.02	Liftoff and pitch-over
3	2.60	Abort motor tail off
4	10.00	Begin reorientation
5	21.00	Jettison tower
6	22.11	Jettison Forward Bay Cover
7	24.50	Deploy drogues
8	30.50	Deploy mains
9	51.67	30 ft/sec Descent
10	99.04	Crew Module touchdown

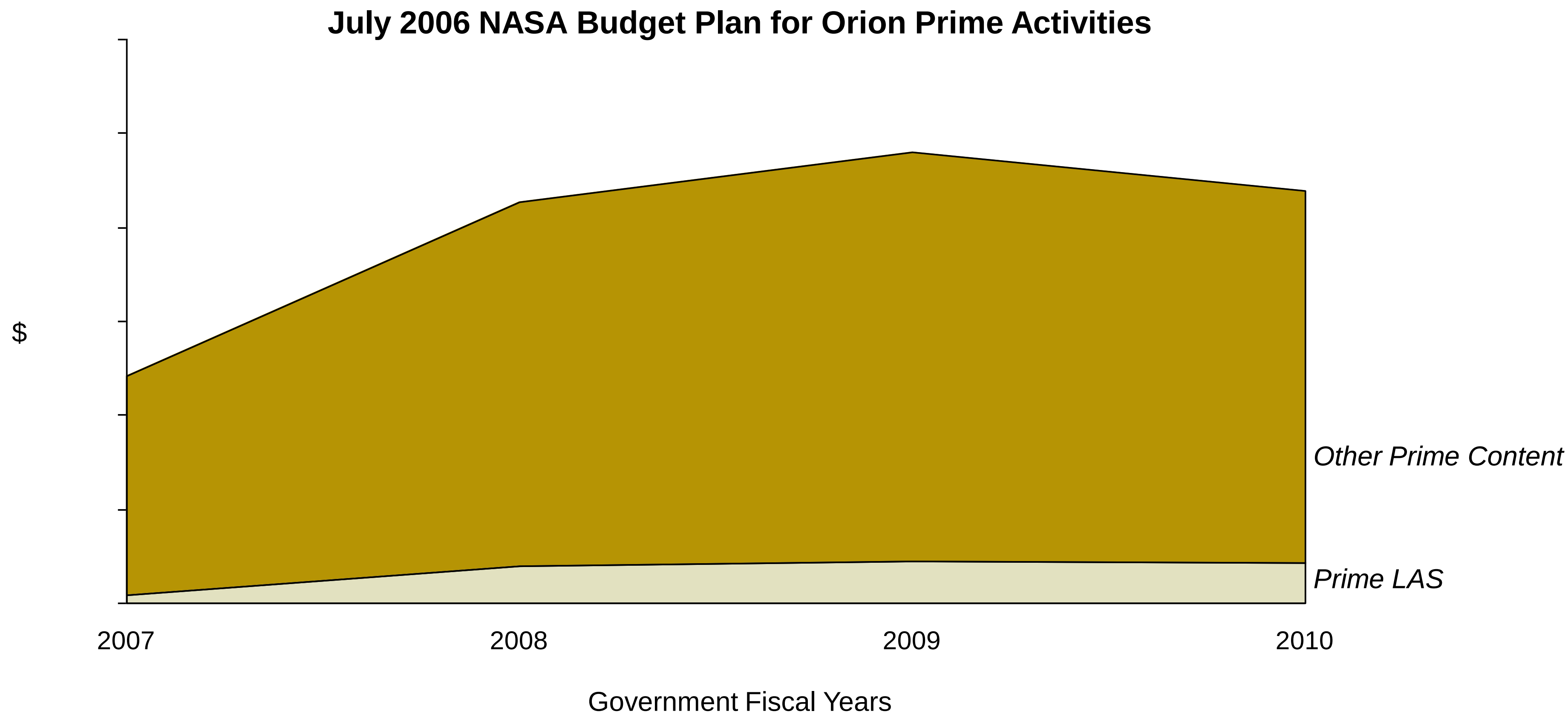


The original plan was for PA-1 to occur 23 September 2008; a little more than two years after contract award

ID	Task Name	Duration	Start	Finish
1	Lockheed Martin (LM) wins Crew Exploration Vehicle (CEV) contract	0 days	Fri 8/25/06	Fri 8/25/06
2	CEV Contract Team Organized	11 days	Fri 8/25/06	Fri 9/8/06
3	Review Analysis Cycle-3 Reconciliation	72 days	Mon 9/11/06	Tue 12/19/06
4	Mass scrub	34 days	Wed 12/20/06	Mon 2/5/07
5	**Mass scrub closure**	**6 days**	**Mon 2/5/07**	**Tue 2/13/07**
6	LM Engineering Review Board (ERB)	0 days	Mon 2/5/07	Mon 2/5/07
7	Prepare CxP Outbrief	4 days	Tue 2/6/07	Fri 2/9/07
8	CxP Outbrief	0 days	Fri 2/9/07	Fri 2/9/07
9	Prepare CEV Project Control Board (CPCB) Outbrief	2 days	Mon 2/12/07	Tue 2/13/07
10	CPCB Outbrief	0 days	Tue 2/13/07	Tue 2/13/07
11	Work accomplishing System Design Review	155 days	Wed 2/14/07	Tue 9/18/07
12	SDR captured in Cradle	0 days	Tue 9/18/07	Tue 9/18/07
13	**Build LAS Flight Equivalent Unit**	**180 days**	**Wed 9/19/07**	**Tue 5/27/08**
14	ACM Development	180 days	Wed 9/19/07	Tue 5/27/08
15	Jettison Motor Development	110 days	Wed 9/19/07	Tue 2/19/08
16	Abort Motor Development	110 days	Wed 9/19/07	Tue 2/19/08
17	LAS Software Development	180 days	Wed 9/19/07	Tue 5/27/08
18	Build CM test article	110 days	Wed 9/19/07	Tue 2/19/08
19	Integration, Verification and Operations	155 days	Wed 2/20/08	Tue 9/23/08
20	PA-1 Launch	0 days	Tue 9/23/08	Tue 9/23/08

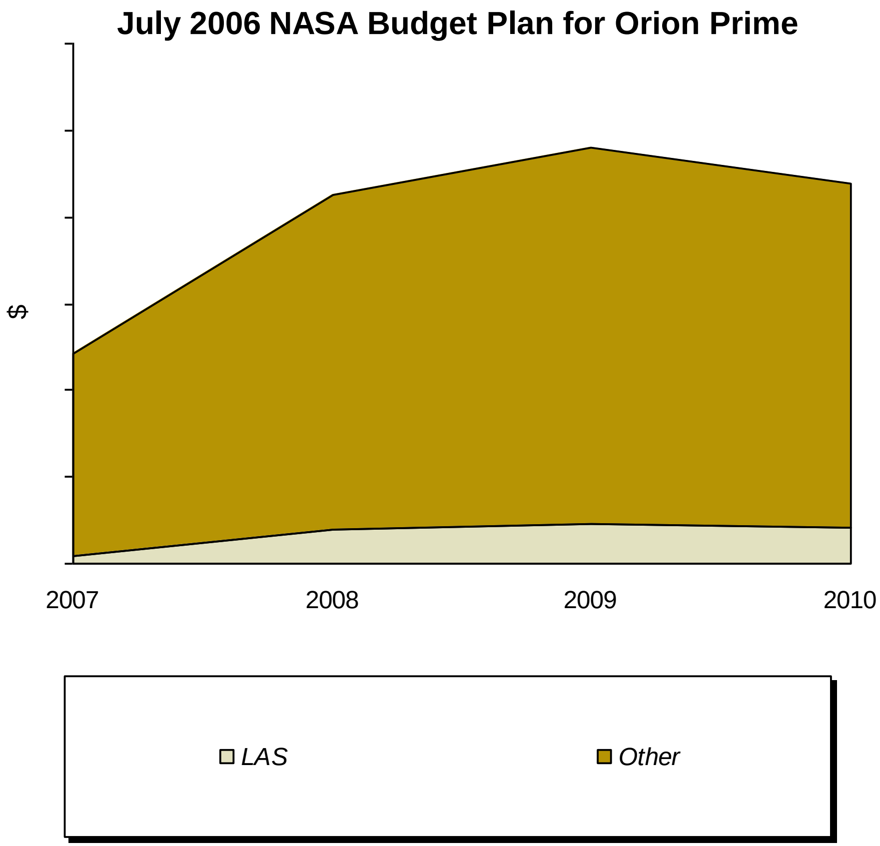


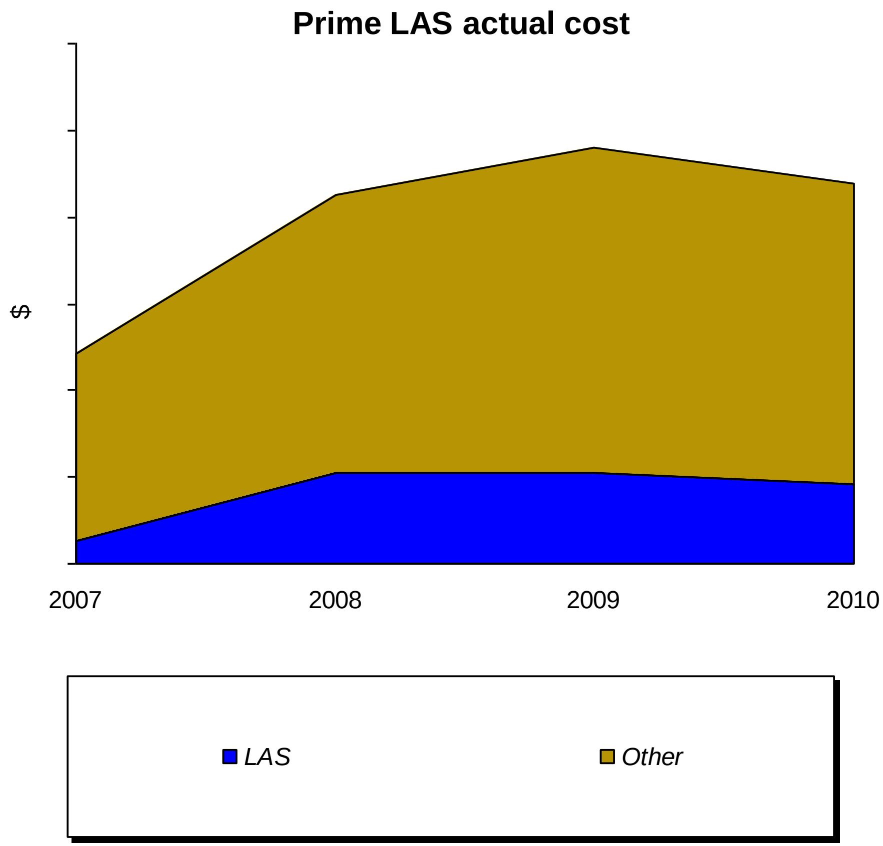
The original plan for LAS development was a small subset of the overall project budget for the Prime contract



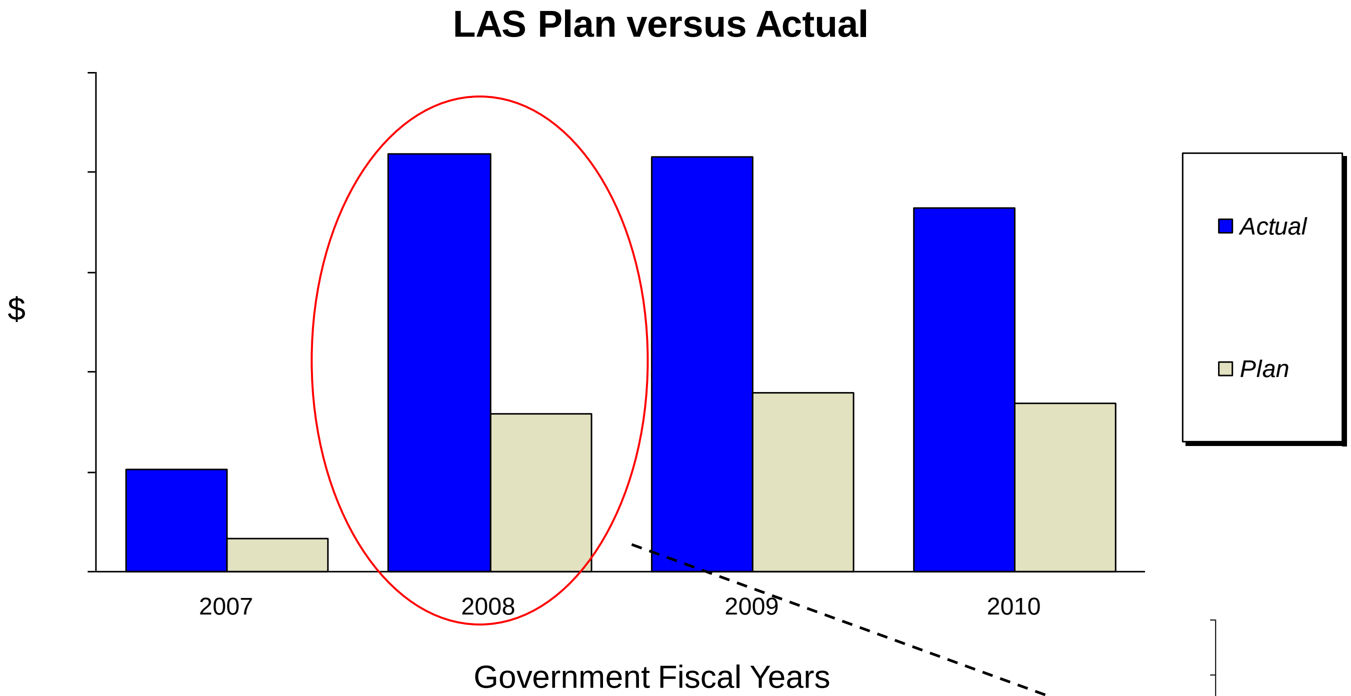
Note: The Prime Contract is approximately 80% of the total Orion budget

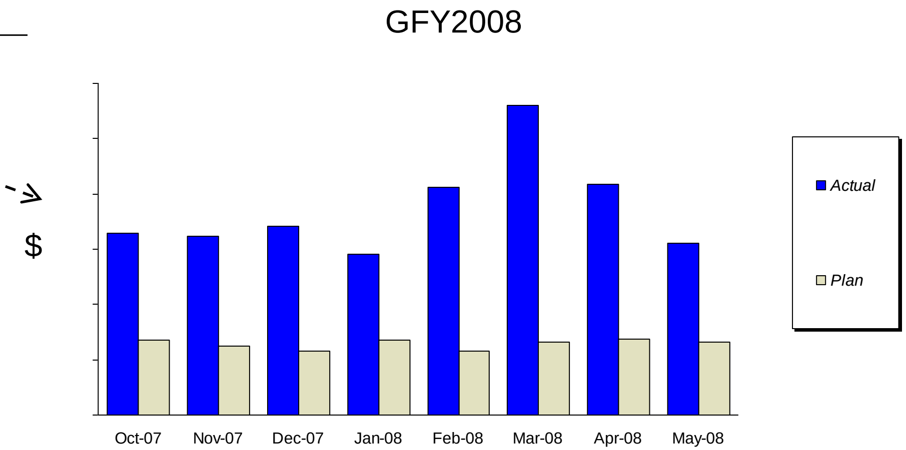
The actual cost for the LAS development exceeded the original plan by more than double





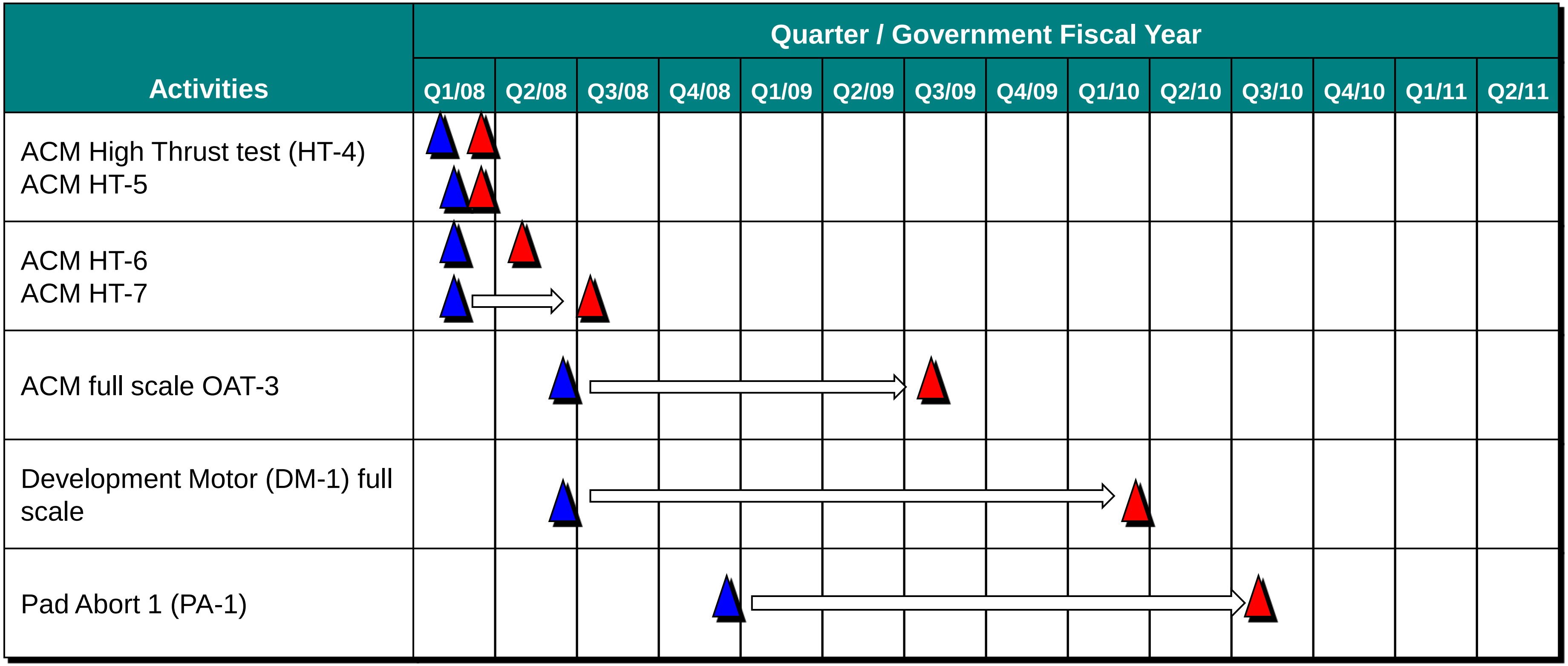
The actual cost for LAS exceeded the budget by more than double





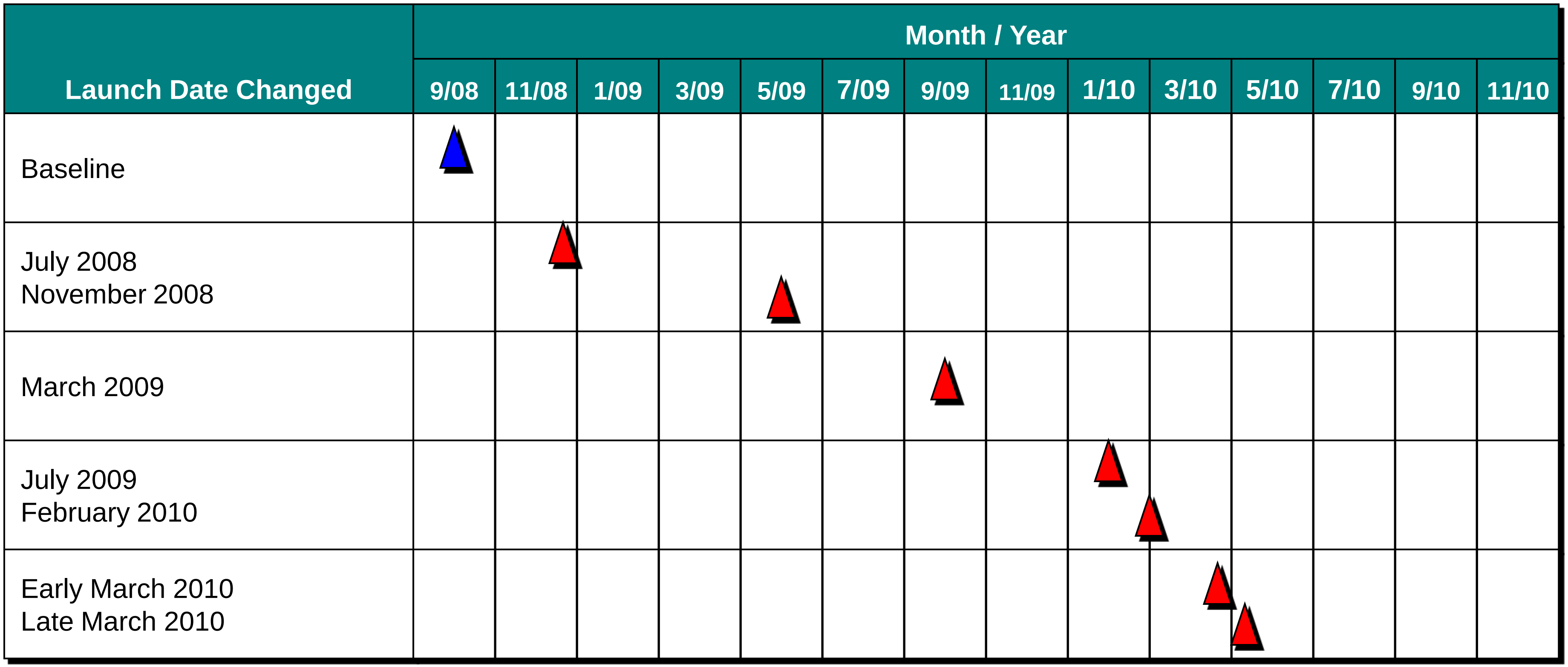
The schedule also slipped demonstrating the relationship between cost over runs and schedule slips

Realized ACM development test plan



The slips to the high visibility PA-1 happened incrementally over the years, but not as the result of an integrated analysis

Incremental slips to PA-1 launch date



The primary cause of the incremental nature of the slips was the lack of an integrated master schedule

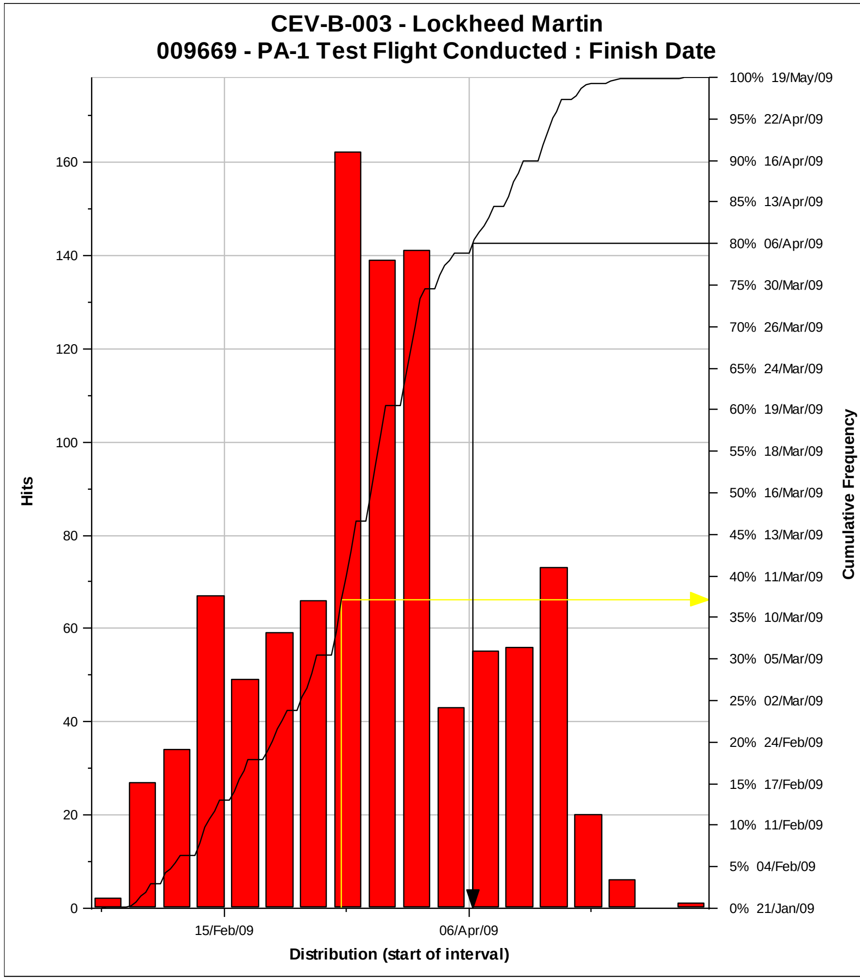
- The Pad Abort (PA-1) schedule was maintained by Non Prime contractors
- The Prime held the main vehicle development schedule
- The linkage between the development of the Attitude Control Motor (ACM) and its usage for PA-1 was apparent because the schedules were not linked
- It only became apparent once slips in ACM development started to drive the schedule for PA-1 to the right
- This did not occur until the third year of the project (2008)

Even without an IMS to better understand dependencies Booz Allen's assessment of PA-1 forecast a considerable slip

- In October 2007, used Oracle's Primavera Risk Analysis (PertMaster) to conduct a schedule analysis for PA-1
  - At the time PA-1 was targeted to occur on September 23, 2008
- Our schedule sensitivity analysis showed little chance of this occurring
- A less than 1% probability of finishing before February 09, 2009
- A 50% probability of finishing on March 23, 2009 was given, with a maximum of May 11, 2009
- At an 80% confidence level; we showed April 01, 2009 as the likely date
- May 20, 2009 is now the planning date because the ACM development schedule has encountered significant challenges
- Without technical input the original analysis did not model the probability of HT-7 failing in April, 2008 four months before the original PA-1 launch date

The original analysis showed an 80% confidence in a PA-1 date of April 2009

- At the time our analysis showed a date of April 2009, NASA was still planning on a September 2008 launch
- Actual launch was not until May 2010
- Again the 2007 Booz Allen PA-1 schedule assessment did not capture the dependency or risks for ACM development



Data	
Finish Date of:	
009669 - PA-1 Test Flight Conducted	
Analysis	
Simulation:	Latin Hypercube
Iterations:	1000
Convergence at mean	
Mean Plan Finish Date:	
Converged in 200 iterations	
(variation < 0.1% over 100 iterations)	
Mean Total Plan Cost:	
Converged in 200 iterations	
(variation < 0.1% over 100 iterations)	
Statistics	
Minimum:	21/Jan/09
Maximum:	19/May/09
Mean:	15/Mar/09
Std Deviation:	22.79
Bar Width:	week
Highlighters	
80%	06/Apr/09
Deterministic (10/Mar/09)	37%

The LAS had low Technical Readiness Level (TRL) design features at Authority to Proceed (ATP) which drove cost and schedule

- Two of the LAS subsystems had a low TRL
- The TRL for the reverse flow nozzles used on the Abort Motor is 4
  - Component and/or breadboard validation in laboratory environment
- Reverse flow manifold technology is new technology

Note: Using NASA's TRL as a reference point

Source: NASA's own assessment

The ACM had an even lower TRL than the Abort Motor's reverse nozzle technology

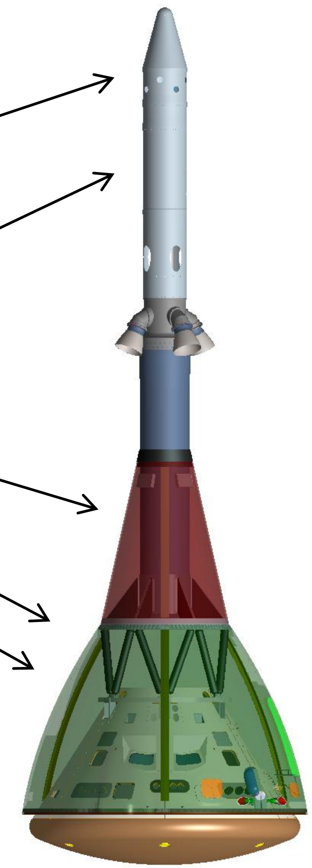
- The LAS Active Control System has a TRL of 3
  - Analytical and experimental critical function and/or characteristic proof of concept
- The exact combination of burn time, thrust level, manifold arrangement, number of nozzles, nozzle materials, and the algorithm to be developed had never been demonstrated before
- The combination of features created the potential for complex systems interaction
- Any failures or anomalies during the development testing from components up to an integrated motor put the schedule at risk

ACM being integrated at White Sands Missile Range

Furthermore there were design changes which also complicated development

- Design Changes from 2007 through 2008

Design	Original	Change
Attitude Control Motor (ACM)	Ti case, Thermal battery	Resized Thermal Protection System (TPS) and skirts, steel case, Li Ion battery
Canard	Functional canard and mechanism	Replaced by shell
Adapter	Two part assembly with gusset plates and joint at Mid Ring	Composite cone with metallic end fittings
Retention & Release (R&R) Ring	Composite	Aluminum
R&R Bracket	Did not allow for mechanism installation	Mechanism installation included
Ogive Panels & Splices	3 each	4 each
Boost Protective Cover (BPC)	Existed	Removed



Low Technology Readiness Levels are a red flag for estimation of cost

- Since NASA proposed TRL as a scale in 1989, there has been increasing interest in its effects on development costs of projects
- Based on many studies, it can be confidently said that TRL may affect development costs
- It can also be said that TRL is more of a risk driver than a cost element
  - Typical projects start at TRL 5 or maybe 4
  - DoD has been criticized by GAO for trying to bring very low TRL systems into projects because it results in large cost over runs
- There is much that is not known about the steps that must be taken to mature the technology sufficiently that a product using it will perform reliably
- The less known about a product or process, the more error likely in any estimate of its cost
- Neither NAFCOM nor SEER have a parameter exactly equal to TRL

NAFCOM and SEER users are frequently handed TRL information to relate back to their respective model's parameters

- NAFCOM users relate TRL to:
  - 8 levels of "new design"

    The LAT Phase 2 cost template used a scale from 1 to 10

    The definitions remained the same, however, the NAFCOM system level new design and NAFCOM component level new design were broken out in the cost template
  - 3 levels of integration complexity
- SEER users relate TRL information back to:
  - 13 levels of "design complexity"
  - Developer capability & experience
  - Development tools & practices
  - New design

Within SEER the parameter that is often considered when TRL needs to be modeled is Design Complexity

- Important to note the Design Complexity is not a proxy for TRL
- Design Complexity runs from Very Low to Very High (13 levels)
  - Focuses on complexity of the design effort and/or the manufacturing process
  - Ties to notions such as “new concepts,” “outside the state-of-the-art,” “requires inventions,” and “parallel multiple development efforts”
- Complexity set to Nominal corresponds to a TRL equal to 5
- Again low TRL is more a risk driver than a cost driver
- Consider the output from the parametric model as an answer <u>before risk is applied</u>
- Actual cost may then grow from 110% to 400% higher than the likely cost model output if risks are realized

Note: The range of 110% to 400% was established by a Tecolote study from 2005.

A study on the maturation of low TRL aeronautics technologies shows the time allotted for maturing the LAS was aggressive

- The February 2008 and May 2008 dates were required to meet a September 2008 target date
  - The Prime contract awarded August 2006
- "If we knew what we were doing, it wouldn't be called research" – Albert Einstein
- The reverse flow nozzle technology on the Abort Motor was a TRL of 4
  - Should be expected to achieve TRL 6 in 35 months
  - Was given approximately 18 months
  - Took 30 months to complete
- The ACM had a TRL of 3
  - Should be expected to achieve TRL 6 in 52 months
  - Was given approximately 20 months
  - Took 42 months to complete

Note: One aeronautics technology removed from the data set because it was an outlier in terms of the number of years required: Tilt rotor Technology

Source: Peisen, Deborah and Catherine Schulz, SAIC Report on Aeronautics TRL, Task Order 221, November, 1999

The Abort Motor was not successfully test on the ground until November 2008

- The original September 2008 date for PA-1 - actual demonstration of the Abort Motor in flight - was not achievable
- If the Abort Motor development was the critical path for the completion of the SDU and launch of PA-1, PA-1 could not have happened earlier than early 2009
- By the time the Abort Motor design was demonstrated on the ground the target for PA-1 was May 20, 2009
- This new date did not take the effect of the ACM development test failure earlier that year

An ACM test unit failed High Thrust test number 7 (HT-7) which was intended to demonstrate current HT valve design

- The HT 7 test commanded one thruster in a fixed manner to achieve a decreased-to-increased level of thrust throughout the test, while the second thruster was expected to respond in order to demonstrate the closed-loop pressure control algorithm
- After HT 7 was initiated, the two thrusters appeared to function properly up until about 5.5 seconds into the test
- At that point the motor chamber pressure ramped from ~2,000 psi to ~3,200 psi in ~30 milliseconds, causing one of the test article safety burst discs to rupture
- No injuries and no facility damage resulted from this event

The best practice for creating a schedule on a development project is to account for risk

- For example in a low TRL development effort, one should anticipate that one of the tests could fail
- If there is a test failure one can anticipate several things will occur
- There will be:
  - A failure investigation
  - Design changes
  - Analysis and testing to confirm design changes
  - Integrated Product Team (IPT) approval to proceed
- The final step is a milestone, but for each of the first three steps a duration could be estimated using a least duration, likely duration and most duration estimate developed by technical subject matter experts

As an example let us examine the high thrust tests for the ACM

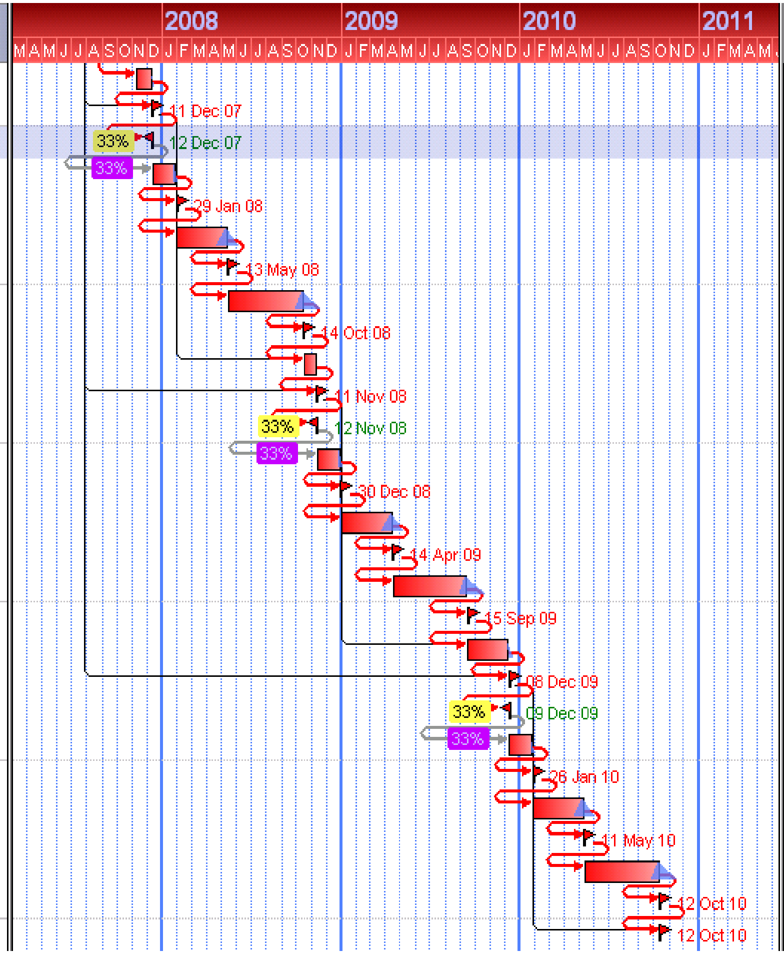
- Originally the schedule was constructed as a simple chain of planned events
- In the case of the ACM the first three high thrust tests were all completed without incident, then the fourth test failed
- The failure investigation drove a design change which delayed the project nine months
- The failure investigation lasted forty-six days: 04/14/08-06/18/08
- Re-test of the new design added another two months to the schedule
- It was almost a full year before ACM development was back on track

Probabilistic branching can be used to model test failure

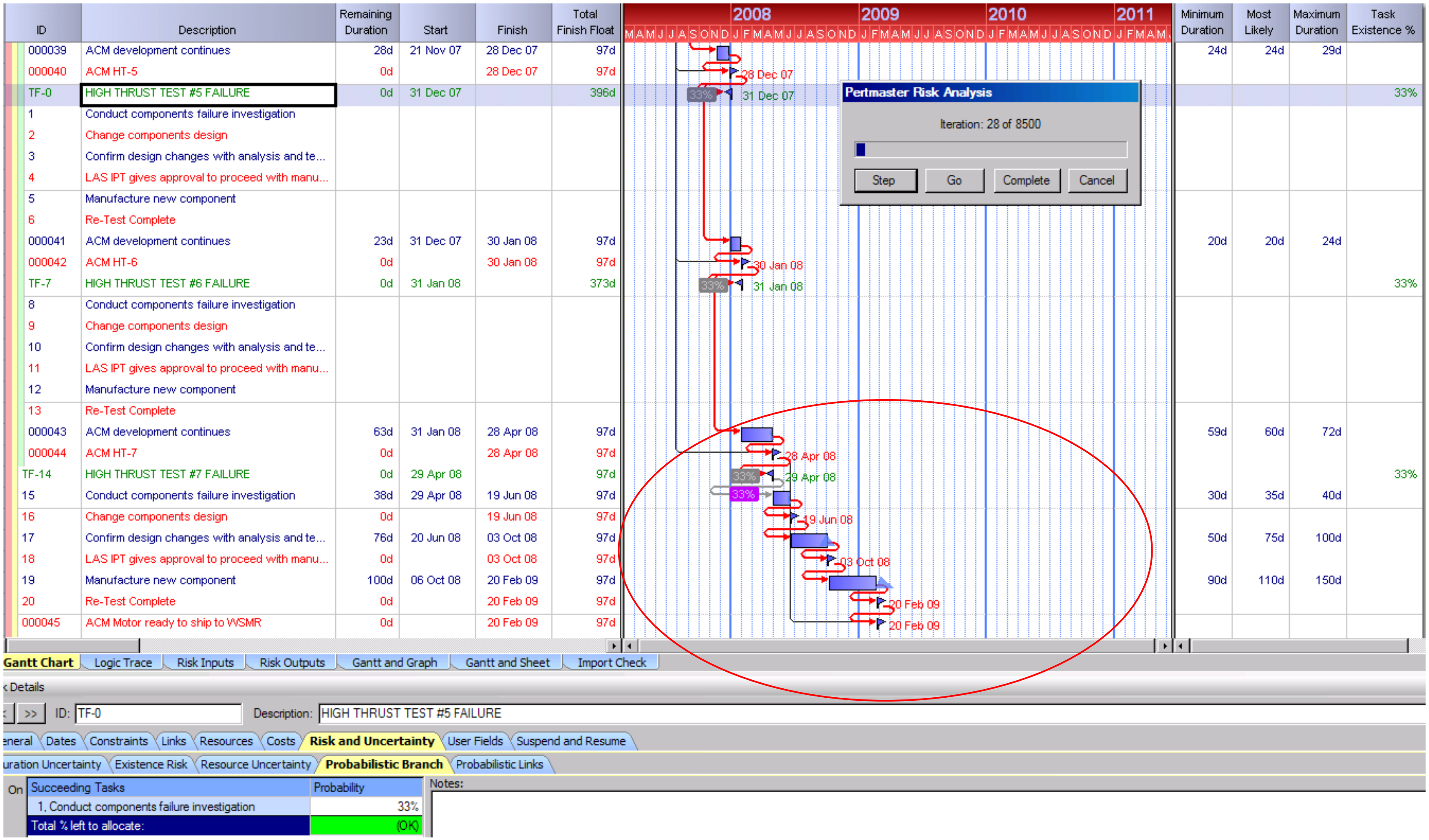
- Each test failure was modeled as a risk with a 33% chance of occurrence
  - Each time the risk occurred, a series of branched activities were associated with it
  - Duration uncertainty ranges were provided as well
- In this schedule example, the ACM was not on the critical path. However, once test failures were introduced, the ACM hit the critical path numerous times, which reflects reality

Below is the risk-impacted schedule prior to the analysis

ID	Description	Remaining Duration	Start	Finish	Total Finish Float	Minimum Duration	Most Likely	Maximum Duration	Task Existence %
000039	ACM development continues	24d	08 Nov 07	11 Dec 07	0d	24d	24d	29d	
000040	ACM HT-5	0d		11 Dec 07	0d				
TF-0	HIGH THRUST TEST #5 FAILURE	0d	12 Dec 07		0d				33%
1	Conduct components failure investigation	35d	12 Dec 07	29 Jan 08	0d	30d	35d	40d	
2	Change components design	0d		29 Jan 08	0d				
3	Confirm design changes with analysis and te...	75d	30 Jan 08	13 May 08	0d	50d	75d	100d	
4	LAS IPT gives approval to proceed with manu...	0d		13 May 08	0d				
5	Manufacture new component	110d	14 May 08	14 Oct 08	0d	90d	110d	150d	
6	Re-Test Complete	0d		14 Oct 08	0d				
000041	ACM development continues	20d	15 Oct 08	11 Nov 08	0d	20d	20d	24d	
000042	ACM HT-6	0d		11 Nov 08	0d				
TF-7	HIGH THRUST TEST #6 FAILURE	0d	12 Nov 08		0d				33%
8	Conduct components failure investigation	35d	12 Nov 08	30 Dec 08	0d	30d	35d	40d	
9	Change components design	0d		30 Dec 08	0d				
10	Confirm design changes with analysis and te...	75d	31 Dec 08	14 Apr 09	0d	50d	75d	100d	
11	LAS IPT gives approval to proceed with manu...	0d		14 Apr 09	0d				
12	Manufacture new component	110d	15 Apr 09	15 Sep 09	0d	90d	110d	150d	
13	Re-Test Complete	0d		15 Sep 09	0d				
000043	ACM development continues	60d	16 Sep 09	08 Dec 09	0d	59d	60d	72d	
000044	ACM HT-7	0d		08 Dec 09	0d				
TF-14	HIGH THRUST TEST #7 FAILURE	0d	09 Dec 09		0d				33%
15	Conduct components failure investigation	35d	09 Dec 09	26 Jan 10	0d	30d	35d	40d	
16	Change components design	0d		26 Jan 10	0d				
17	Confirm design changes with analysis and te...	75d	27 Jan 10	11 May 10	0d	50d	75d	100d	
18	LAS IPT gives approval to proceed with manu...	0d		11 May 10	0d				
19	Manufacture new component	110d	12 May 10	12 Oct 10	0d	90d	110d	150d	
20	Re-Test Complete	0d		12 Oct 10	0d				
000045	ACM Motor ready to ship to WSMR	0d		12 Oct 10	0d				

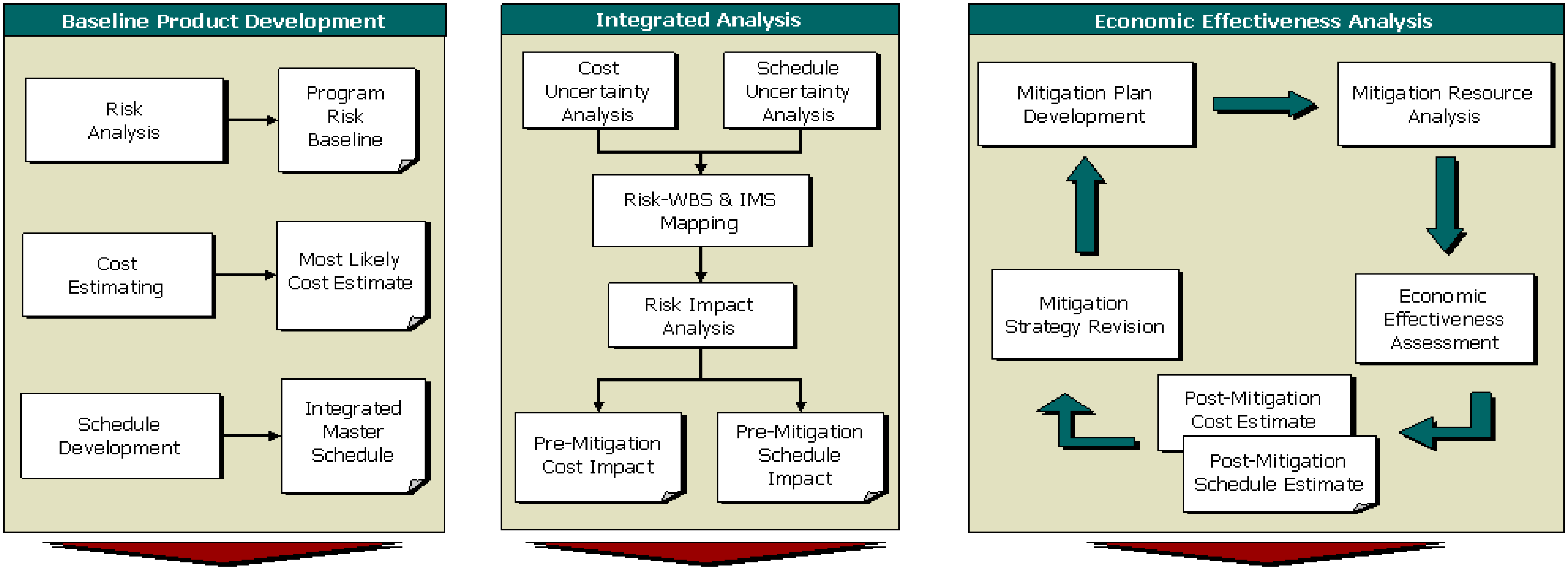


The Monte Carlo simulates Test Failures occurring with the template of activities following as well



An example of a programmatic methodology for handling cost and schedule risk is Booz Allen's proprietary RISC – IQ offering

Risk Integrated with Schedule and Cost – Intelligent Quantification



Objective: Assess completeness of Baseline documentation and understand existing processes.

Objective: Provide insight into where risks affect the program and uncover their true impacts.

Objective: Compare program risk profile at mitigation completion to determine outstanding risk exposure.

RISC-IQ uncovers critical insights into the effects of risk on the program baseline

Capability	Description	Benefit
1. Risk Baseline Audit	▸ Review existing state of risks & opportunities ▸ Assess completeness of baseline documentation	▸ Enables understanding of existing process ▸ Validate ability to integrate risks & opportunities across program ▸ Assess duplication of risks and quality of impact descriptions
2. Risk Distribution Analysis	▸ Map risks to WBS and Integrated Master Schedule (IMS) ▸ Ties risks to programmatic milestones ▸ Can use standing USG (e.g. DAU) risk categories for comparison	▸ Provides insight into where risks affect the program ▸ Used to ensure completeness of baseline and facilitate new risk identification ▸ Aligns to US DOD program management best practices ▸ Enables decision tree analysis to learn why risks are clustered within WBS elements
3. Risk & Opportunity Impact Quantification	▸ Enhance scoring approach for risks ▸ Conduct probabilistic assessments of risk impacts	▸ Helps to uncover true impacts of program risks ▸ Uses risk impact assessments to determine more realistic program cost and schedule ▸ Assesses the impact of risk BEFORE mitigation, to assist with the development of remediation strategies
4. Mitigation Effectiveness Analysis	▸ Estimate cost and schedule needs of proposed mitigation plans ▸ Compare mitigation resource needs with impact assessments	▸ Determine mitigation plan realism and scope ▸ Assess resource implications of selected plans ▸ Compare program risk profile at mitigation completion to determine overall effectiveness

RISC-IQ ties risks to specific line items in the program master schedule to identify threats to the critical path

Master Schedule Risk Map

Line Items	Schedule Item	Risk Type 1	Risk Type 2	Risk Type 3	Risk Type 4	Risk Type 5	…	Risks per Line Item
2.0	**SBN**	1	1			2		4
3.0	**Mission**	2		2	1			5
4.0	**Ground**		1			4		5
4.1	**GSE**	3			2			5
4.2	**Program Mgmt**	4		2				6
4.3	**SED**	5	1		2			8
4.4	**Via Sat**	6		2		1		9
4.5	**SOG**	1		3				4
5.0	**Launch**	1	1		1	2		5
5.1	**Booster**							0
5.2	**Supplemental**							0
…n	**…**							…

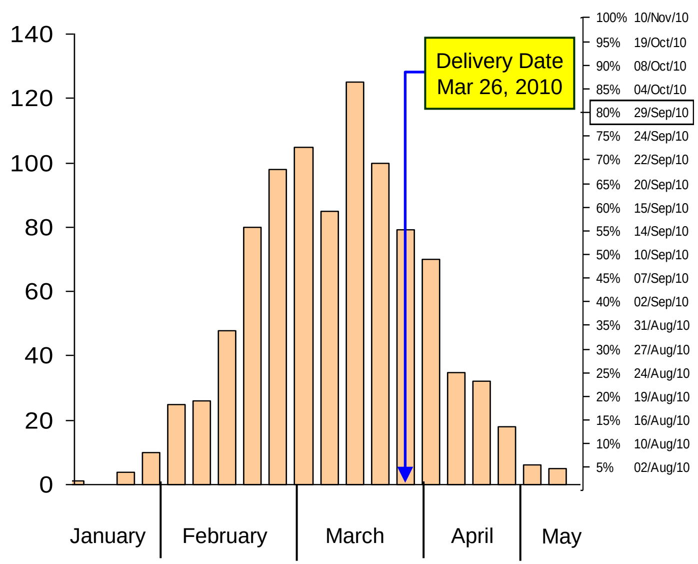
Discussion

- Mapping risks to the schedule identifies cascade effects causing delays in delivery and increases in costs
- By addressing work packages on the critical path management can identify immediate actions and resources…
- …to preempt risks that will lead to carrying costs of underutilized staff and equipment (e.g. the standing army)

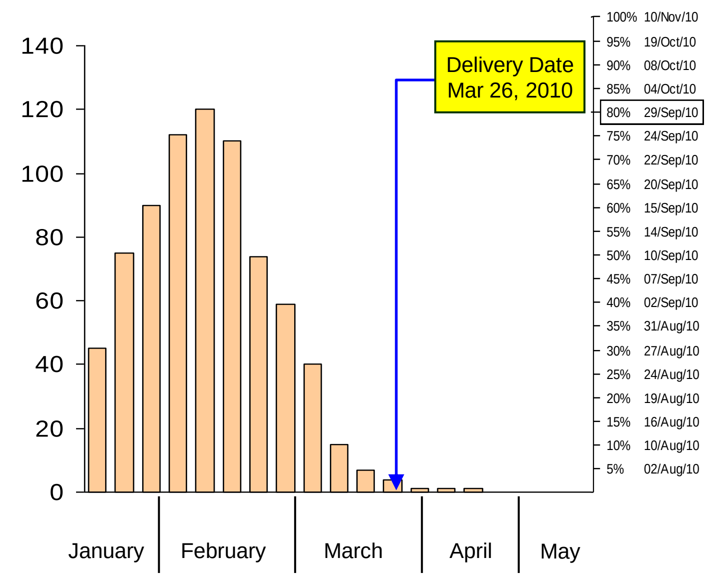
Simulations and statistical analysis identifies where risks can be mitigated to stabilize the schedule…

Client Example

Unmitigated Impact to Critical Path



Mitigated Impact to Critical Path



Discussion

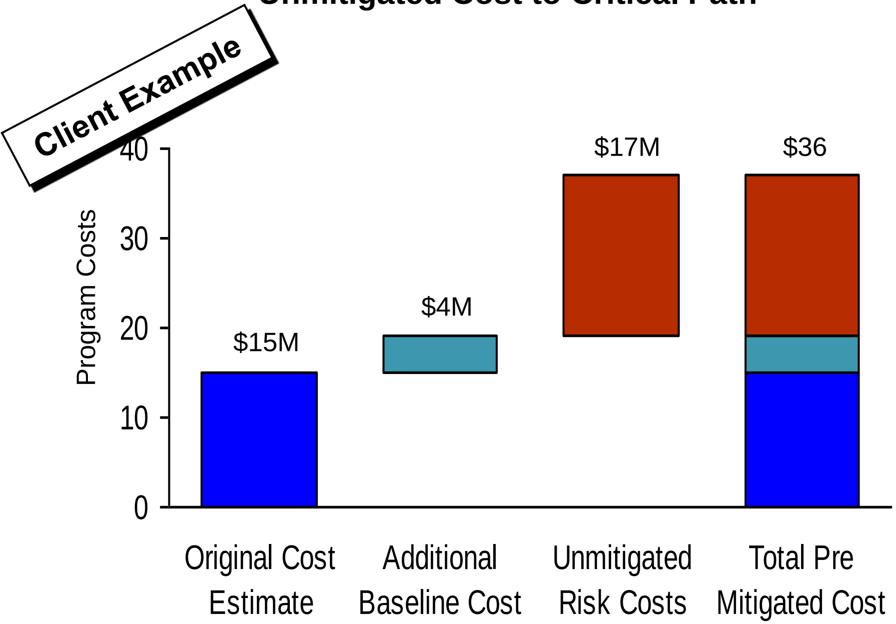
- Schedule risk analysis identifies likelihood of program extending 2-months after deadline
- Potentially leading to missed award fees and possible delay penalties from the government

Discussion

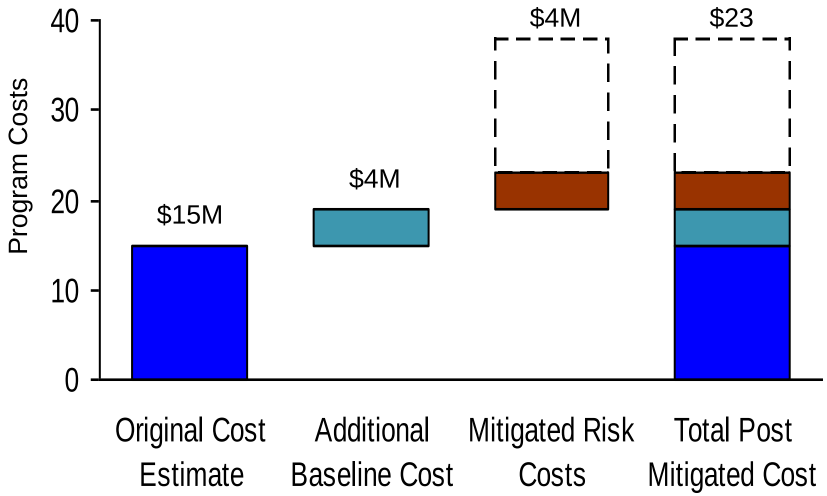
- Risk mitigation allows informed decision making as to confidence level project should be funded to ensure on-time delivery
- Demonstrates diminishing returns of mitigation for tailing risks

… and address identified cost overruns

Unmitigated Cost to Critical Path



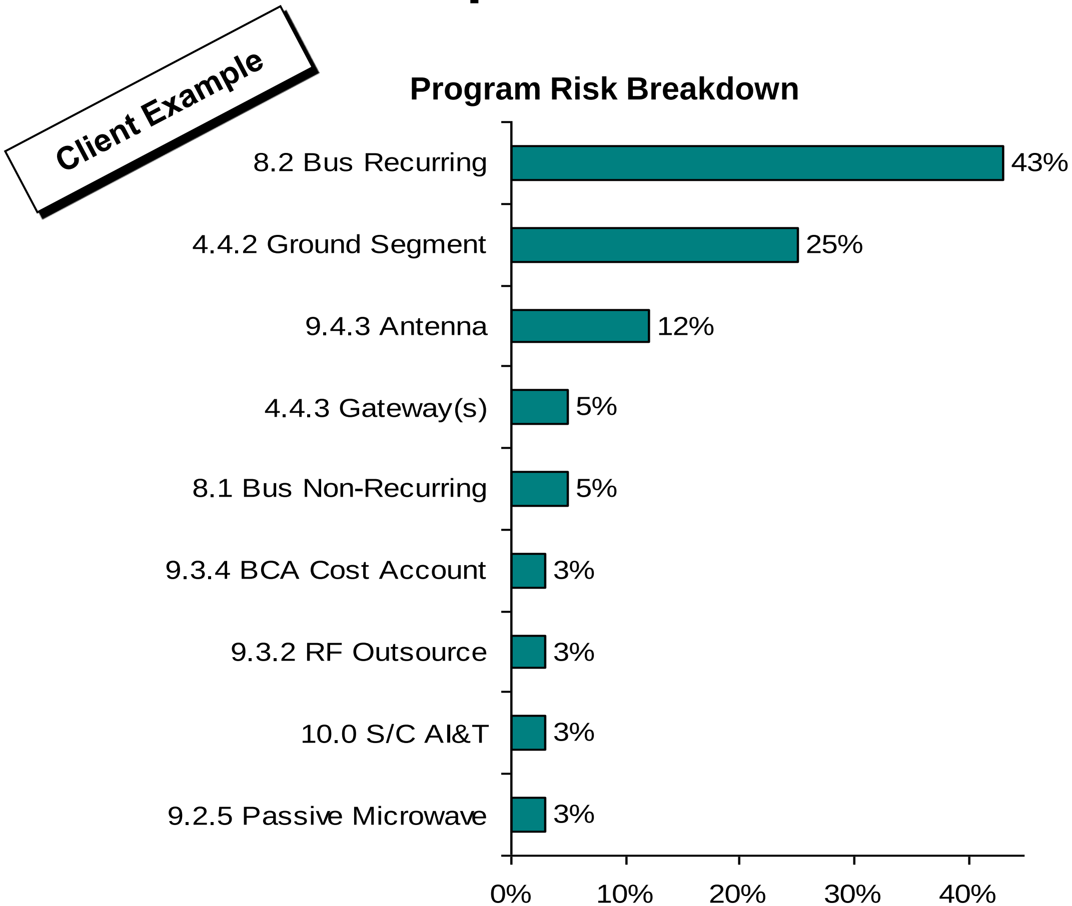
Mitigated Cost to **Critical Path**



Discussion
▸ Client baseline is underreporting risk and costs by $4M in its program baseline ▸ With additional (at 85% confidence) ~$20M in risk-related costs expected

Discussion
▸ Client avoids $13M in risk related costs, and the process of requesting additional government funds ▸ Early adoption of RISC-IQ provides transparency into the budget and total program costs

RISC-IQ enables leadership to prioritize mitigation and investment resources to specific work-streams



Discussion

- RISC-IQ allows the Program Manager to quickly identify biggest risks to the critical path
- Risk mitigation decisions are based on the time and resources to resolve
- Detailed mitigation plans are built by RISC-IQ analysts as risks are identified…
- …and the costs to resolve are contingent to completing the mitigation planning process

RISC-IQ is an integrated solution for program leadership providing insights into three key areas

- Program Performance
  - Combines previously disparate program analysis and execution into an actionable framework for the program manager
  - Requires dialog and collaboration between engineering, scheduling and management groups
  - Creates a "total risk profile" to programs to fully assess potential delays to delivery and increases in cost
- Program Investment
  - Provides a framework to develop detailed plans for risk mitigation and identify associated costs
  - Tracks progress of investment against specific mitigation activities
  - Assists decision makers in prioritizing investment dollars against high impact risks and effects
- Program Oversight
  - Responds to government policy guidance and industry best practices in risk management
  - Provides auditable trail of risks, cost changes and schedule progress for industry and government clients
  - Creates transparency in developing program budget and reserve requirements when used prior to program start date

To summarize the lessons learned one should take an integrated approach when assessing a development project

- Establish baseline costs
  – Parametric models work best for a TRL of 5 or greater
- Identify risks
  – If using parametric estimates for TRL below 5, assume significant cost growth to the parametric result is possible
- Estimate the cost and schedule impacts of the risks
  – If you have a test plan for a development activity, allow for the possibility of a test failure
- Evaluate the implication of the results to the project
- Develop mitigation steps to insure against these risks
  – May require removing content