Generic Cost Profiles Based on Actual Costs in NASA CADRes

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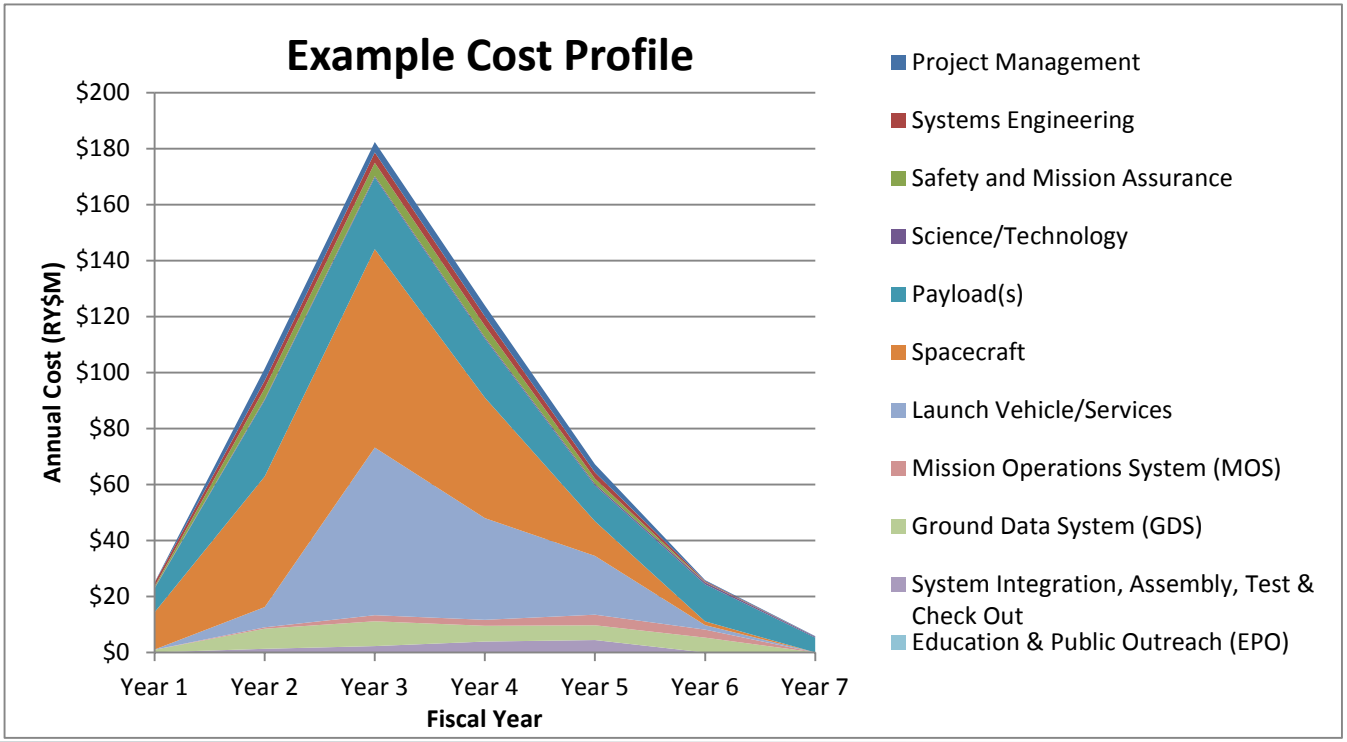
Introduction

- An important part of many cost estimates is the spreading of the cost by year
- Whitley[1] presented a process for fitting equations to actual cost data for multiple APL projects
- This paper expands that work to cost data from the NASA Cost Analysis Data Requirement (CADRe) documents to develop a set of generic profiles



1) Sally Whitley, "Spending Profile Analysis for NASA Integrated Project Assessments", *2012 IEEE Aerospace Conference*, 2012

CADRe Cost Data Overview

- CADRe is a three part document that:
  - *Describes a NASA project, at a given point in time, to allow an independent entity to estimate the project's life cycle cost (Parts A & B)*
  - *Captures the NASA project's projected and actual life cycle costs in both a project specific and standardized NASA Cost Estimating Work Breakdown Structure (WBS) (Part C)*
    - Costs captured in Real Year (Then Year) dollars
- A CADRe prepared at launch will reflect the complete development cost actuals

NASA WBS Elements	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Total
Project Total	$25,067	$100,108	$182,337	$123,993	$67,257	$27,383	$5,885	$534,804
Project Management	$105	$4,257	$3,730	$3,888	$2,937	$312	$172	$15,400
Systems Engineering	$1,264	$2,750	$3,697	$3,409	$2,185	$355	$28	$13,689
Safety and Mission Assurance	$540	$3,843	$4,739	$4,032	$1,869	$143	$0	$15,165
Science/Technology	$204	$417	$520	$530	$575	$679	$310	$3,234
Payload(s)	$8,541	$27,219	$25,576	$21,067	$12,783	$13,243	$5,310	$113,739
Spacecraft	$13,307	$46,655	$70,869	$43,035	$12,370	$1,333	$7	$187,577
Launch Vehicle/Services	$76	$7,224	$59,870	$36,316	$20,991	$1,601	$0	$127,522
Mission Operations System (MOS)	$0	$496	$2,168	$2,133	$3,780	$2,859	$0	$11,436
Ground Data System (GDS)	$928	$7,179	$8,861	$5,631	$5,276	$5,306	$58	$33,240
System Integration, Assembly, Test & Check Out	$107	$1,366	$2,326	$3,950	$4,491	$52	$0	$12,293
Education & Public Outreach	$0	$0	$9	$0	$0	$0		$9
Reserves	$0	$0	$0	$0	$0	$1,500	$0	$1,500

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NASA Project Phases

- Project Phases from NPR 7120.5E - *NASA Space Flight Program and Project Management Requirements*
  - *Pre-Phase A: Concept Studies*
  - *Phase A: Concept & Technology Development*
  - *Phase B: Preliminary Design & Technology Completion*
  - *Phase C: Final Design & Fabrication*
  - *Phase D: System Assembly, Integration & Test, Launch & Checkout*
  - *Phase E: Operations & Sustainment*
  - *Phase F: Closeout*

- A total project budget known as the Agency Baseline Commitment is established at the start of Phase C
  - *A phasing by year is established but can changed due to reallocation of Unallocated Future Expenses (reserves) held both within the project and above the project*

- This study examines cost profiles for the primary development phases, B-D

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Full Mission Data Set

- Started with CADRes for all available (27) science missions launch CADRes with complete Phase B-D development costs by Fiscal Year
  - *Excluded missions with 2 years or less of development (e.g. NEAR)*

Project	Launch Date	Project	Launch Date
AIM	4/25/2007	MRO	8/12/2005
CloudSat	4/28/2006	New Horizons	1/19/2006
CONTOUR	7/3/2002	OCO	2/24/2009
Dawn	9/27/2007	Odyssey	4/7/2001
Deep Impact	1/12/2005	Phoenix	8/4/2007
Fermi (GLAST)	6/11/2008	Spitzer (SIRTF)	8/25/2003
GALEX	4/28/2003	Stardust	2/7/1999
Genesis	8/8/2001	STEREO	10/25/2006
GRACE	3/17/2002	Swift	11/20/2004
GRAIL	10/9/2011	THEMIS	2/17/2007
Kepler	3/6/2009	TRMM	11/27/1997
LRO	6/17/2009	WISE	12/14/2009
MER	6/10/2003	WMAP	6/30/2001

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Data Processing

- Start with CADRe data by FY and by WBS
  - *Phases B-D only*
  - *Inflate everything to FY12$*

- Combine WBS elements into logical WBS combinations
  - *Project Management, Systems Engineering, Mission Assurance (PM/SE/MA)*
  - *Science, Mission Operations System, Ground Data System (Science/MOS/GDS)*
  - *Payloads*
  - *Flight System, System I&T (FS/I&T)*
  - *Project Total excluding Launch Services and EPO*
  - *Project Total including Launch Services and EPO*

- Convert WBS combination data to cumulative percent cost and percent time
  - *Each data point represents the cumulative percent cost spent at a cumulative percent time*

- Combine all projects into single data set of percent cost vs. percent time

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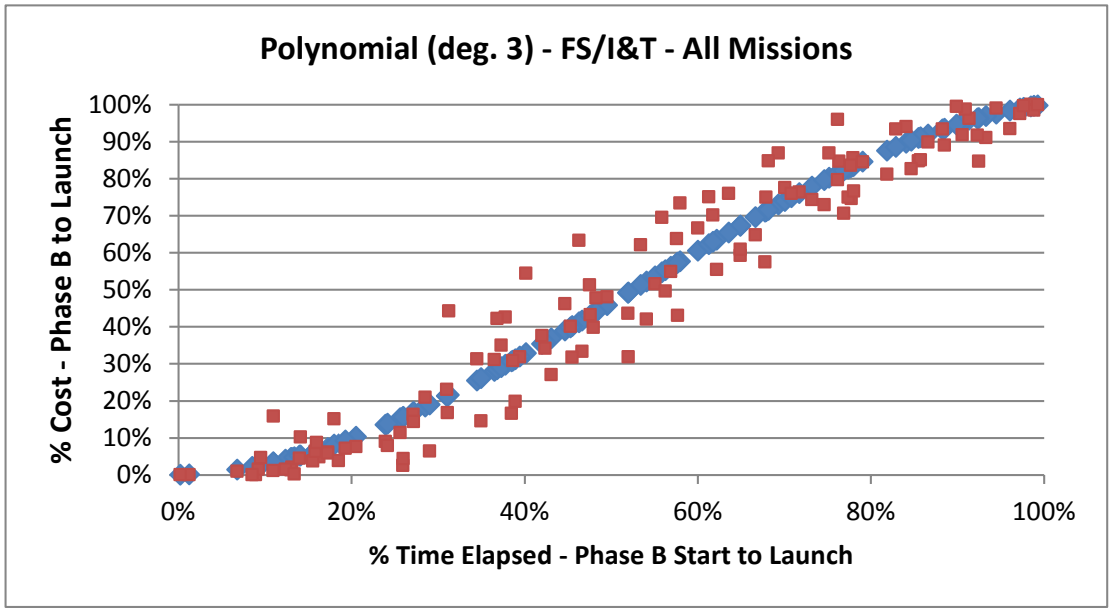
Functional Forms Examined

- Majority of study done with polynomials (2nd and 3rd order)
  - *Intuitive and provided good flexibility of fit*

$$f(T) = AT + BT^2$$

or

$$f(T) = AT + BT^2 + CT^3$$



- Also looked at Weibull and Beta forms
  - *Have been used by other authors[2] and/or cited in cost estimating literature*
  - *Performance was typically equal to or worse than polynomial*
  - *Excel Solver was not always able to find a solution*

2) Eric Burgess, *"Time Phasing Methods and Metrics"*, *37th Annual DoD Cost Analysis Symposium,* 2004

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Regression Methodology

- Minimize the sum of squared additive errors:

$$\sum (\varepsilon_i)^2 = \sum (y_i - f(x_i))^2$$

  – *Where* y_i *are actuals,* $f(x_i)$ *are estimates and* ε_i *are errors*

- Constraints enforced
  – *100% cost at 100% time*
  – *Minimum cost of 0%*
  – *Maximum cost of 100%*

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Regression Metrics

- Pearson's correlation squared between actuals and estimates

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (y_i - \hat{y})}{\sum_{i=1}^{n} (y_i - \bar{y})^2}$$

- Standard Error of the Estimate (SEE)

$$SEE = \sqrt{\frac{1}{n-m} \sum_{k=1}^{n} \left(f(x_i) - y_i \right)^2}$$

- Average bias of estimate

$$Bias = \frac{1}{n} \sum \left(f(x_i) - y_i \right)$$

- Percent cost at 50% time

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Polynomial Fit Statistics

Data Set (No.Msns/Data Pts)		Coefficients			Goodness of Fit Metrics			% Cost at 50% Time
All Missions (26 / 120)								
WBS	Equation Type	a	b	c	R^2	SEE	Bias	
PM/SE/MA	Polynomial (deg. 2)	0.59082	0.40918	-	0.954	6.6%	0.2%	40%
Sci/MOS/GDS	Polynomial (deg. 2)	0.16455	0.83545	-	0.931	7.8%	0.4%	29%
FS/I&T	Polynomial (deg. 3)	0.00018	2.66743	-1.66761	0.953	7.4%	0.4%	46%
Instruments	Polynomial (deg. 3)	0.51575	1.98610	-1.50185	0.948	8.0%	0.2%	57%
Total Mission (No LV/EPO)	Polynomial (deg. 3)	0.14905	2.29370	-1.44275	0.971	5.6%	0.4%	47%
Total Mission (LV/EPO Included)	Polynomial (deg. 3)	0.09365	2.21768	-1.31133	0.965	6.1%	0.3%	44%

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Reduction of Data Set to “Nominal” Projects

- Several projects in the full data set had unique profiles due to issues such as an externally-driven launch delay or protracted stand-down or stretch-out
  - *Eliminated projects with delays that were clearly externally-driven*

Project	Launch Date	Project	Launch Date
AIM	4/25/2007	MRO	8/12/2005
~~CloudSat~~	~~4/28/2006~~	New Horizons	1/19/2006
CONTOUR	7/3/2002	~~OCO~~	~~2/24/2009~~
~~Dawn~~	~~9/27/2007~~	Odyssey	4/7/2001
Deep Impact	1/12/2005	Phoenix	8/4/2007
Fermi (GLAST)	6/11/2008	Spitzer (SIRTF)	8/25/2003
GALEX	4/28/2003	Stardust	2/7/1999
Genesis	8/8/2001	STEREO	10/25/2006
GRACE	3/17/2002	Swift	11/20/2004
GRAIL	10/9/2011	THEMIS	2/17/2007
Kepler	3/6/2009	TRMM	11/27/1997
LRO	6/17/2009	~~WISE~~	~~12/14/2009~~
MER	6/10/2003	WMAP	6/30/2001

Reduces number of missions from 26 to 22

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Reduction of Data Set to “Optimal” Projects

- Eliminated projects with greater than 40% cost growth from Phase B start to launch
  - *May be indicative of a poor starting plan*
  - *Actuals may not represent an optimal profile for a project with a good plan*

Project	Launch Date	Project	Launch Date
~~AIM~~	~~4/25/2007~~	MRO	8/12/2005
~~CloudSat~~	~~4/28/2006~~	New Horizons	1/19/2006
~~CONTOUR~~	~~7/3/2002~~	~~OCO~~	~~2/24/2009~~
~~Dawn~~	~~9/27/2007~~	Odyssey	4/7/2001
Deep Impact	1/12/2005	Phoenix	8/4/2007
~~Fermi (GLAST)~~	~~6/11/2008~~	~~Spitzer (SIRTF)~~	~~8/25/2003~~
~~GALEX~~	~~4/28/2003~~	Stardust	2/7/1999
Genesis	8/8/2001	~~STEREO~~	~~10/25/2006~~
GRACE	3/17/2002	~~Swift~~	~~11/20/2004~~
GRAIL	10/9/2011	THEMIS	2/17/2007
~~Kepler~~	~~3/6/2009~~	TRMM	11/27/1997
LRO	6/17/2009	~~WISE~~	~~12/14/2009~~
~~MER~~	~~6/10/2003~~	WMAP	6/30/2001

Reduces number of missions to 13

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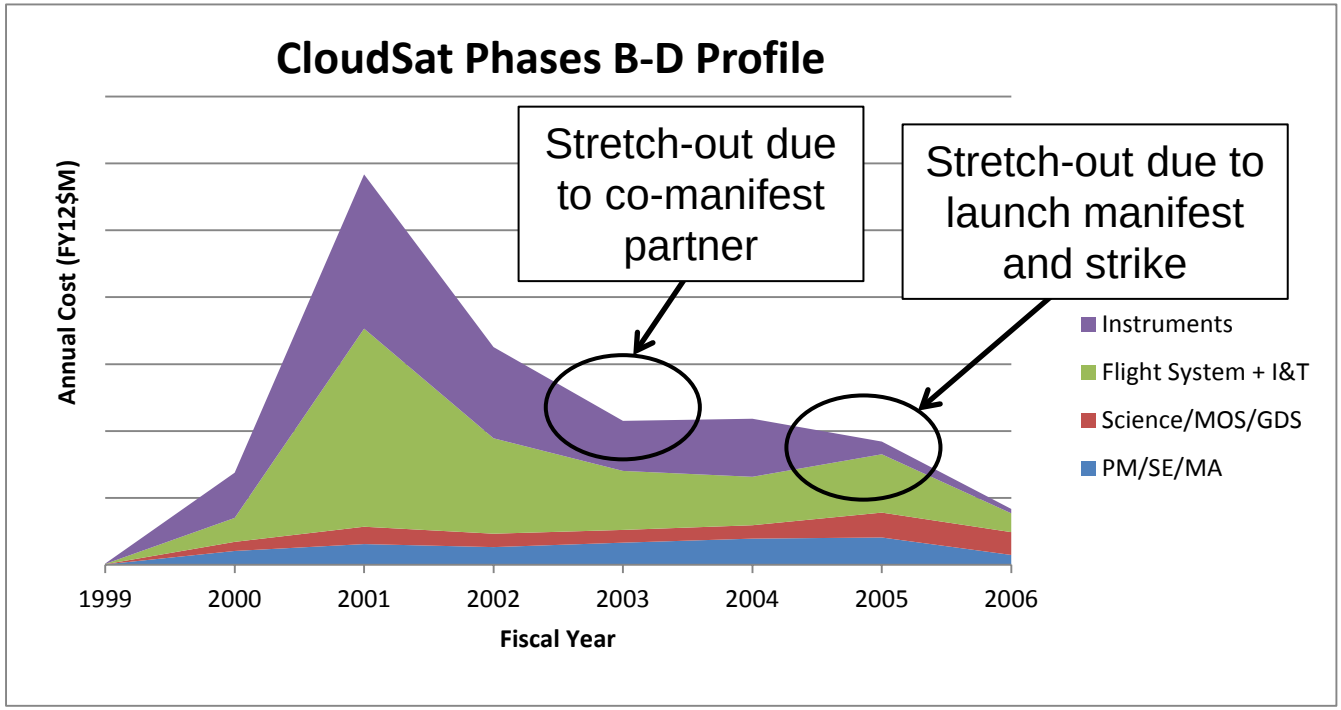
External Delay Example

- The CloudSat project experienced two externally-driven events that distort the actual cost profile
  - *In 2002, spacecraft was placed into storage due to issues with co-manifest partner*
  - *In 2005, after shipment to the launch site, there were additional delays due to manifest issues and a strike against Boeing*



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Results for Reduced Data Sets

WBS	Equation Type	Data Set (No.Msns/Data Pts)	a	b	c	R^2	SEE	Bias	@50% Time
PM/SE/MA	Polynomial (deg. 2)	All Missions (26/120)	0.59082	0.40918	-	0.954	6.6%	0.2%	40%
		Nominal Missions (22/98)	0.57310	0.42690	-	0.947	7.2%	0.2%	39%
		Optimal Missions (13/53)	0.66544	0.42690	-	0.960	6.4%	0.2%	42%
Sci/MOS/GDS	Polynomial (deg. 2)	All Missions (26/120)	0.16455	0.83545	-	0.931	7.8%	0.4%	29%
		Nominal Missions (22/98)	0.12935	0.87065	-	0.928	8.0%	0.4%	28%
		Optimal Missions (13/53)	0.16376	0.83624	-	0.915	8.8%	0.5%	29%
FS/I&T	Polynomial (deg. 3)	All Missions (26/120)	0.00018	2.66743	-1.66761	0.953	7.4%	0.4%	46%
		Nominal Missions (22/98)	-0.02709	2.71933	-1.69224	0.965	6.4%	0.4%	45%
		Optimal Missions (13/53)	-0.02736	2.74936	-1.72201	0.964	6.7%	0.5%	46%
Instruments	Polynomial (deg. 3)	All Missions (26/120)	0.51575	1.98610	-1.50185	0.948	8.0%	0.2%	57%
		Nominal Missions (22/98)	0.39521	2.22806	-1.62327	0.955	7.4%	0.0%	55%
		Optimal Missions (13/53)	0.50412	2.00945	-1.51356	0.944	8.4%	0.2%	57%
Total Mission (No LV/EPO)	Polynomial (deg. 3)	All Missions (26/120)	0.14905	2.29370	-1.44275	0.971	5.6%	0.4%	47%
		Nominal Missions (22/98)	0.07752	2.44175	-1.51927	0.976	5.1%	0.4%	46%
		Optimal Missions (13/53)	0.04947	2.57200	-1.62147	0.976	5.3%	0.4%	47%
Total Mission (LV/EPO Included)	Polynomial (deg. 3)	All Missions (26/120)	0.09365	2.21768	-1.31133	0.965	6.1%	0.3%	44%
		Nominal Missions (22/98)	0.03012	2.32817	-1.35829	0.970	5.7%	0.2%	43%
		Optimal Missions (13/53)	0.00381	2.42232	-1.42613	0.966	6.2%	0.2%	43%

- Significant differences in fit coefficients for the three data sets

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Impact of Constrained Launch Dates

- Projects with launch dates constrained by planetary launch windows might show a different profile shape when compared to unconstrained projects
  - *"Optimal" constrained missions – 6; "Optimal" non-constrained missions – 7*

Data Set (No.Msns/Data Pts)
Optimal Constrained (C) (6/21)
Optimal Non-Constrained (NC) (7/32)

WBS	Equation Type	a	b	c	R^2	SEE	Bias	@50% Time
PM/SE/MA	Polynomial (deg. 2) (C)	0.60779	0.39221	-	0.990	3.2%	0.1%	40%
	Polynomial (deg. 2) (NC)	0.70659	0.29341	-	0.945	7.9%	0.4%	43%
Sci/MOS/GDS	Polynomial (deg. 2) (C)	0.10577	0.89423	-	0.948	6.9%	0.8%	28%
	Polynomial (deg. 2) (NC)	0.20515	0.79485	-	0.903	10.1%	0.3%	30%
FS/I&T	Polynomial (deg. 3) (C)	-0.02395	2.40510	-1.38115	0.949	7.8%	0.5%	42%
	Polynomial (deg. 3) (NC)	-0.02981	2.99468	-1.96487	0.983	5.0%	0.5%	49%
Instruments	Polynomial (deg. 3) (C)	0.33697	2.48481	-1.82178	0.947	8.3%	0.2%	56%
	Polynomial (deg. 3) (NC)	0.54752	1.92234	-1.46986	0.944	8.8%	0.5%	57%
Total Mission (No LV/EPO)	Polynomial (deg. 3) (C)	0.06022	2.32298	-1.38320	0.973	5.6%	0.4%	44%
	Polynomial (deg. 3) (NC)	0.04202	2.74880	-1.79082	0.982	4.8%	0.4%	48%
Total Mission (w/ LV/EPO)	Polynomial (deg. 3) (C)	-0.00352	2.19429	-1.19077	0.968	5.8%	0.3%	40%
	Polynomial (deg. 3) (NC)	0.00947	2.58355	-1.59301	0.971	6.0%	0.1%	45%

- Constrained missions show greater back loading trend (lower percent cost at 50% time)
  - *FS/I&T illustrated on next slide*

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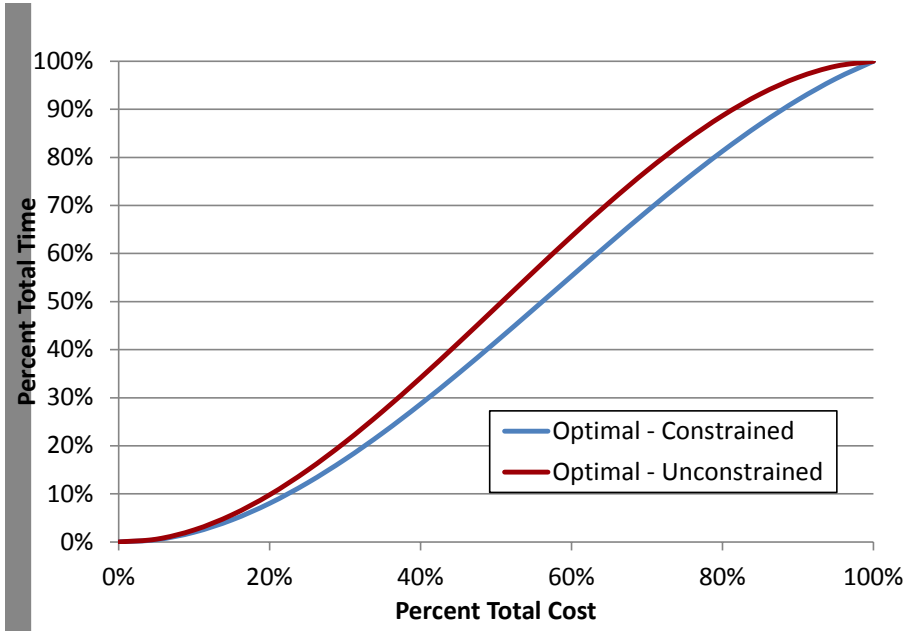
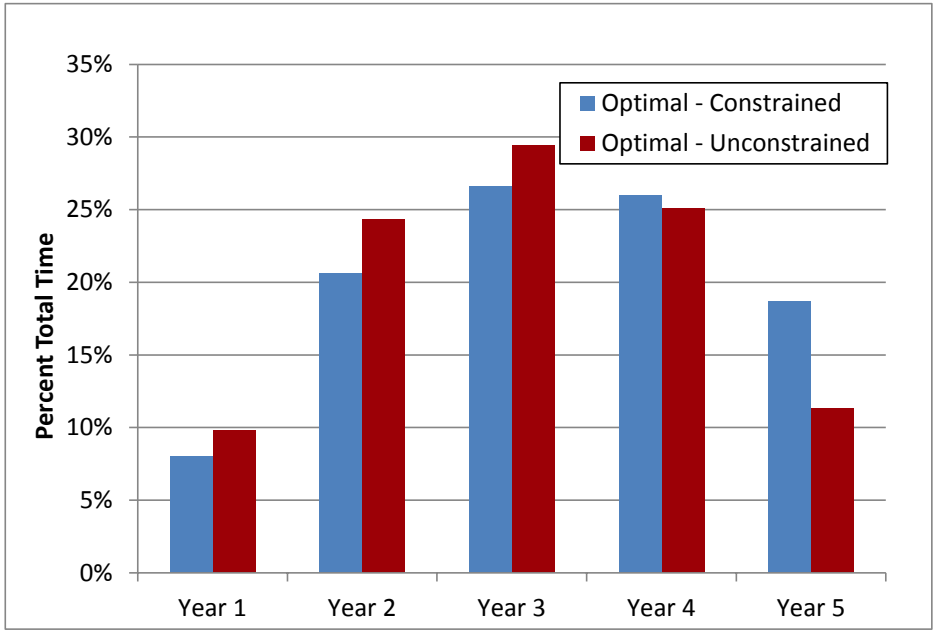
Impact of Constrained Launch Dates

- Comparison of constrained versus non-constrained loading for Flight System and I&T (FS/I&T)
- Unconstrained profile shows more spending in front half of project





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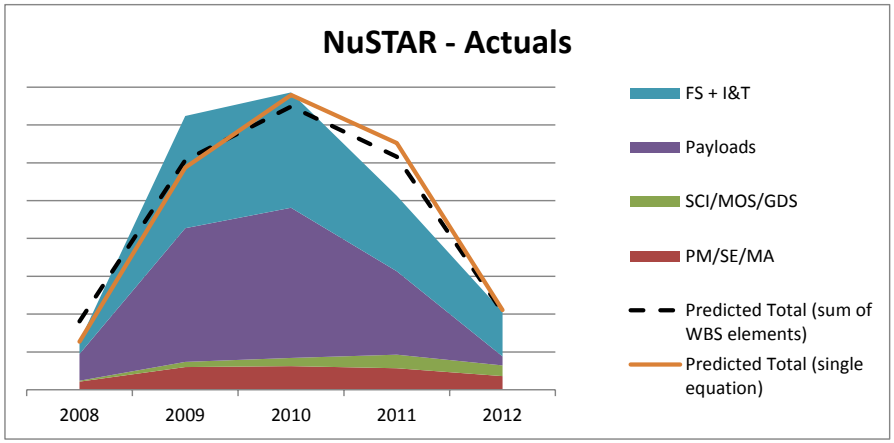
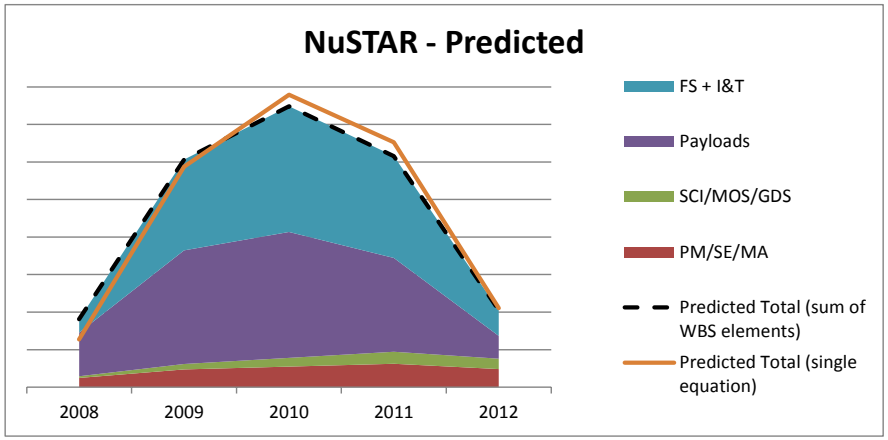
Comparisons with Project Actuals

NuSTAR

- Used equations to predict profiles for a project that was not part of the data set
  - *Use actual totals, then predict spread using unconstrained equations*
  - *Done for individual WBS elements and totaled (black line), and also for project total (orange line)*
  - *Both plots are phases B-D only, excluding launch vehicle and EPO*





- Predictions are lower in year two and higher in year 4
  - *Reflect a less aggressive ramp-up*
  - *Note: total areas are the same since they both add to the project actual total*

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Summary

- Curves derived for spreading costs based on CADRe data from well-behaved projects
  - *Data derived from unmanned science missions*
  - *Note that this data is cost not obligations, so analyst would need to adjust output if obligations are needed*

- Preferred functional form is Polynomial based on fit metrics and ease of use
  - *Fit statistics are equal or better*
  - *Works better with Excel Solver*

- Prefer equations from “Optimal” mission data set
  - *New projects would assume “optimal” conditions at the start*

- Differentiate projects based on constrained or non-constrained launch date
  - *Back-loaded profiles observed for constrained projects consistent with spending additional money during I&T to meet a launch window*

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