Cost and Schedule Uncertainty

Analysis of Growth in Support of JCL

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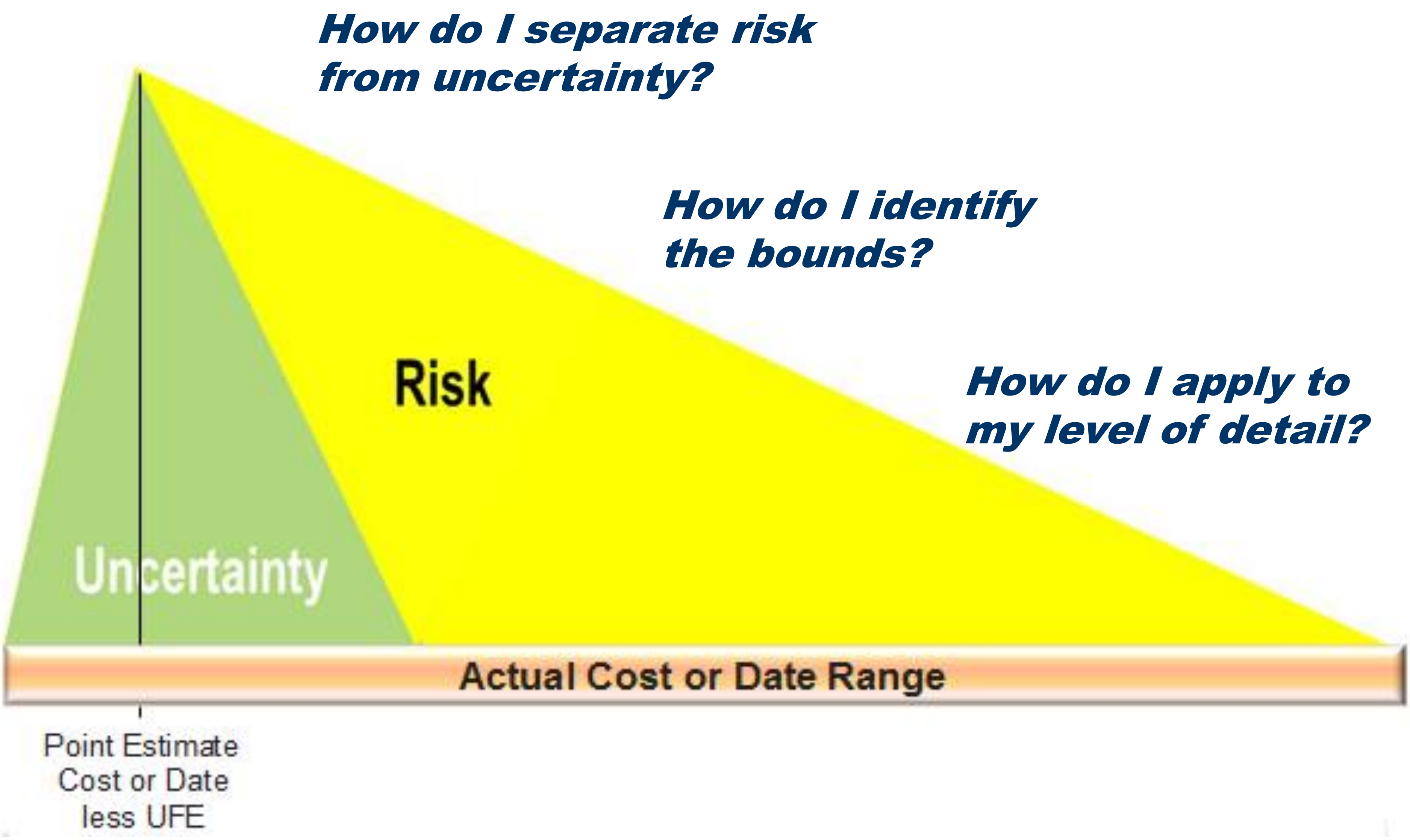
Abstract

NASA formal probabilistic estimating guidance was first mentioned in February 2006 and later codified in 2009 Joint Cost and Schedule Confidence Level (JCL) policy. NASA has been continually making strides to hone the associated best practices and understanding for JCL analysis. One of the issues identified within the JCL construct is the lack of data-driven uncertainty guidance.

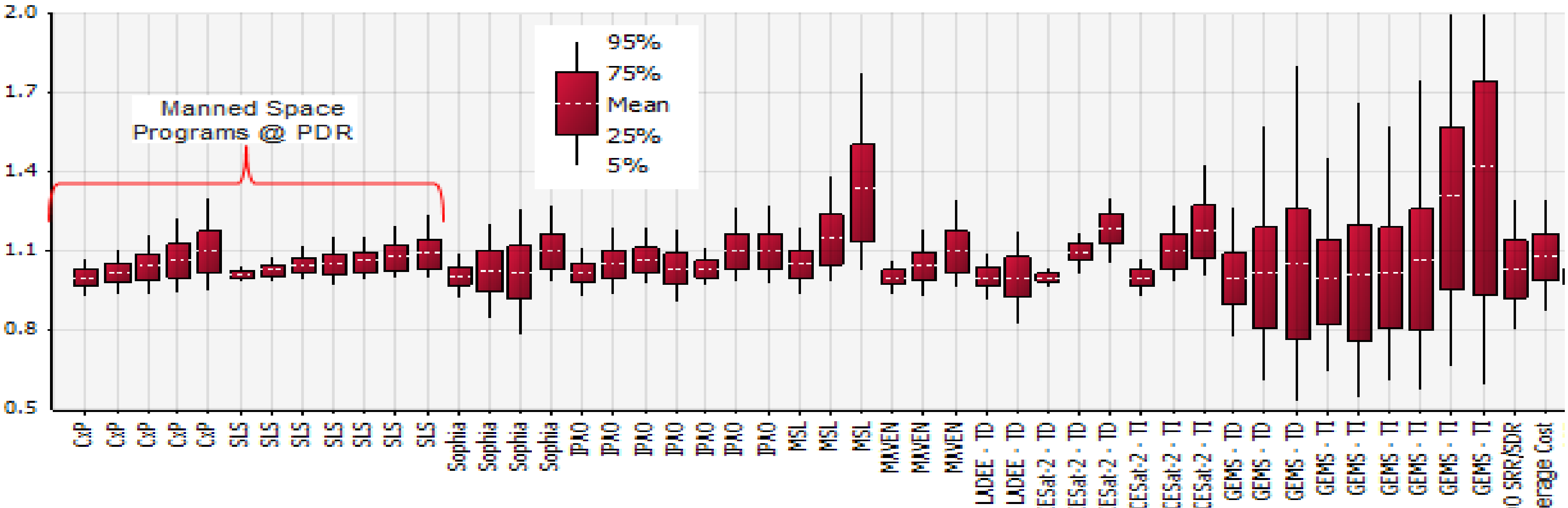
Typically uncertainty is modeled using a three point estimate at an activity or summary level. The low value represents the low extreme of uncertainty, the middle value represents the "most likely" value of the cost or duration, and the high value represents the high extreme of uncertainty. In general, there is not a consistent set of practices or guidelines for how to determine the boundaries or distributions of the "natural" variation of cost and schedules in project development. This has primarily been due to a lack of data, however over the past 7 years through the CADRe initiative NASA has been building a robust archive of project cost, schedule, and technical data at various points in a projects technical maturity. This data provided an opportunity to assess and determine if cost and schedule growth metrics could be developed for use in JCL analysis.

This presentation will provide insight into the analysis process and discuss the data challenges that existed within the study. Initial results of cost and schedule distributions will be provided as well as insight into the impact of complexity and technical maturity. This study provides direct benefits to analysts in developing or reviewing JCL models.

The JCL Modeling Challenge…



The Wild Wild West?



Source: Butts, Glenn, "Uncertainty Approach, " NASA Cost Symposium 2013, August 2013

In general, NASA projects have little consistency in setting the boundaries or distributions of the "natural" variation of cost and schedules

Furthermore, projects have difficulty distinguishing epistemic (discrete risks) in their risk registers from those that are included in natural uncertainty

Our community needs specific data, methodologies, and guidelines to help them determine appropriate levels of task duration and cost variation

In Pursuit of Perfection

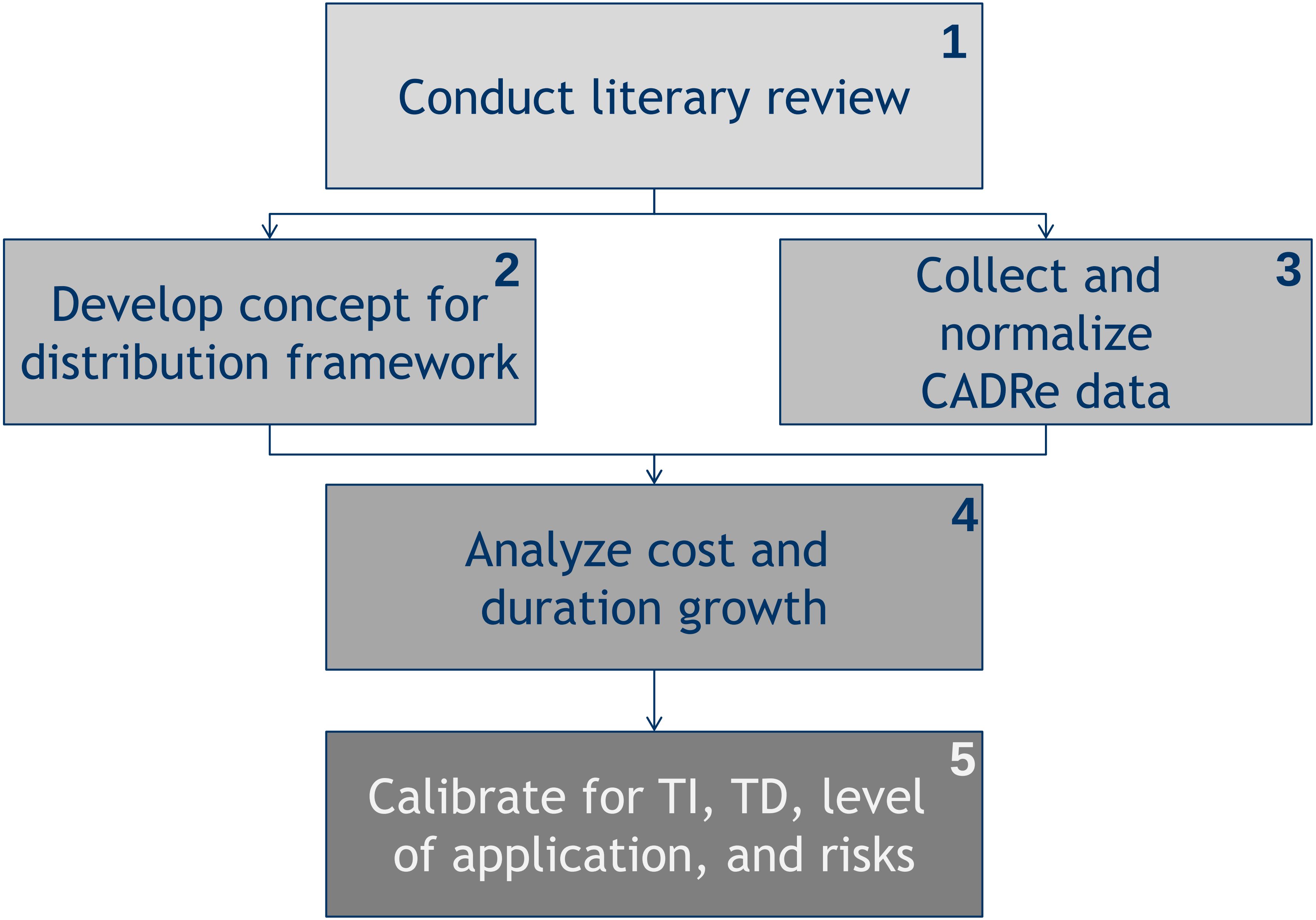
Goal of the NASA OoE/CAD directed study was to determine a set of distributions based on historical data for duration and cost that could be applied to all levels of a project JCL model and account for risk

A Humbling Experience

Key Thoughts at the Beginning of our Journey

- ✓ Don't recreate the wheel
- ✓ Create DATA DRIVEN guidelines
- ✓ Establish framework that is easily understood and can evolve
- ✓ Account for topology/level/behavior
- ✓ Address risk/uncertainty "double accounting"

Our Path…


1
Conduct literary review
2
Develop concept for distribution framework
3
Collect and normalize CADRe data
4
Analyze cost and duration growth
5
Calibrate for TI, TD, level of application, and risks

Cost and Schedule Uncertainty Guidelines

Step 1 – Literary Research

Wide Range of Documents Researched

AACEI 17R-97	Christensen, P., et. al., "Cost Estimate Classification," AACE International Recommended Practice No. 17R-97, American Association for Cost Engineering International, November 2011.
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Filippazzo, 2004	Filippazzo, G., "Complexity Based Cost Estimating Relationships for Space Systems," IEEE Aerospace Conference, 2004.
GAO, 2009	Government Accountability Office, "GAO Cost Estimating and Assessment Guide: Best Practices for Developing and Managing Capital Program Costs," GAO Report GAO-09-3SP, 2009. GAO Cost Estimating and Assessment Guide
Garvey, 2006	Garvey, P., "Introduction to Systems Cost Uncertainty Analysis," MITRE Paper MP 05B0000012, presented at the National Institute of Aerospace Distinguished Lecture Series, May 2005.
Granli, 2009	Granli, O., "Project Uncertainty Management," MIT Open Courseware, Spring 2009.
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LaserLight	Wonica, D., "Estimating Cost Uncertainty when only Baseline Cost is Available," LaserLight Networks, Inc., unknown publication date.
Leach, 2005	Leach, P., "Modeling Uncertainty in Project Scheduling," Proceedings of the 2005 Crystal Ball User Conference, 2005.
Leising, 2011	Leising, C., "Concept Maturity Levels," NASA PPMB, April 2011.
Little, 2006	Little, T., "Schedule Estimation and Uncertainty Surrounding the Cone of Uncertainty," IEEE Software, Published by IEEE Computer Society, May/June 2006.
McConnell, 1996	McConnell, S., "Rapid Development: Taming Wild Software Schedules" Microsoft Press, 1996.
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Research Findings

COST AND SCHEDULE UNCERTAINTY GUIDELINES

Literature Review

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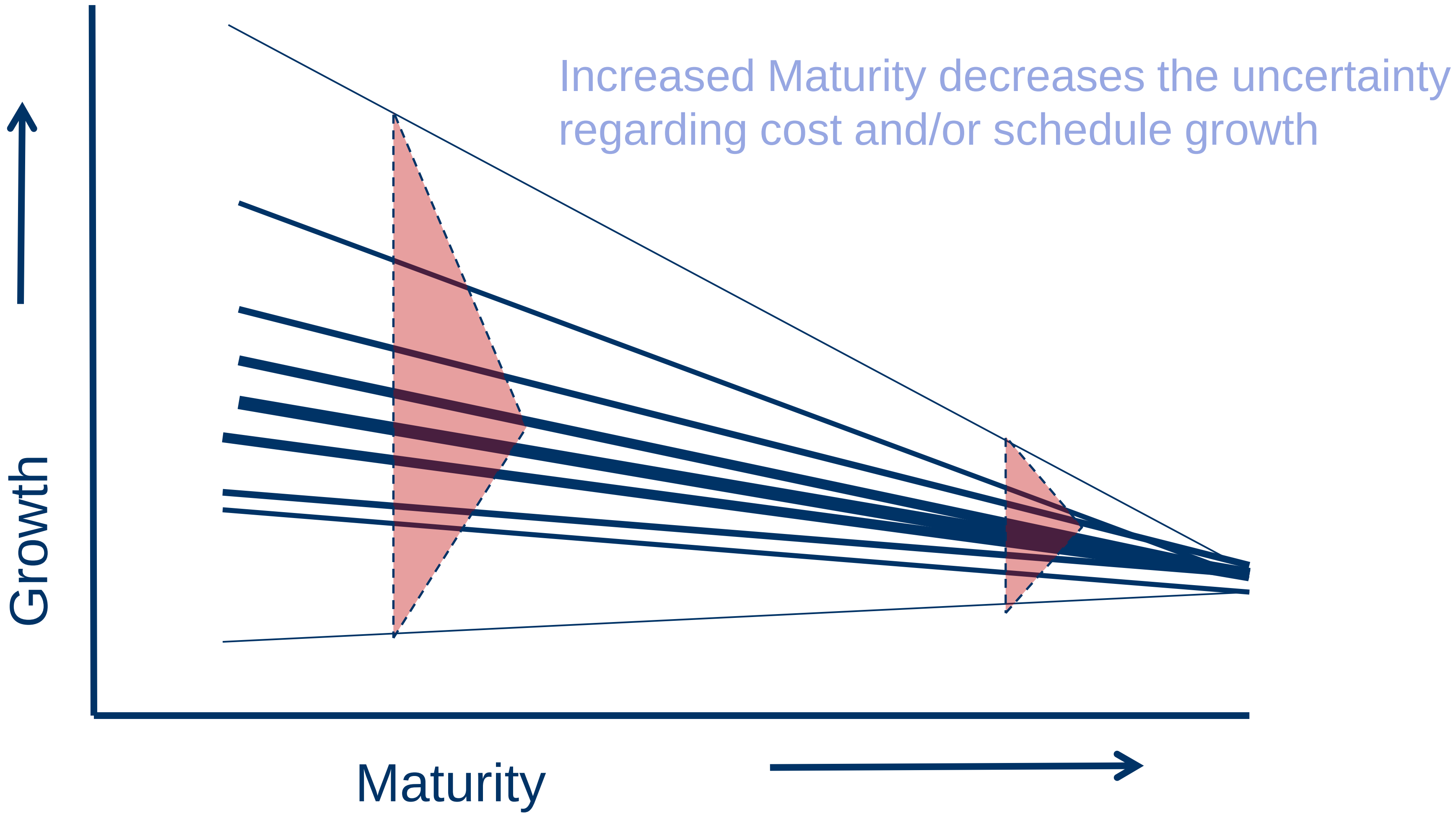
1. Data driven metrics derived based on percentage growth from a specific reference point – typically award
2. Metrics developed at a commodity or specific hardware level (e.g., subsystem)
3. Metrics categorized by level of technical challenge/complexity
4. Ranges decrease as technical understanding (design maturity) increases
5. No current tables are directly applicable to NASA PDR /CDR JCL's

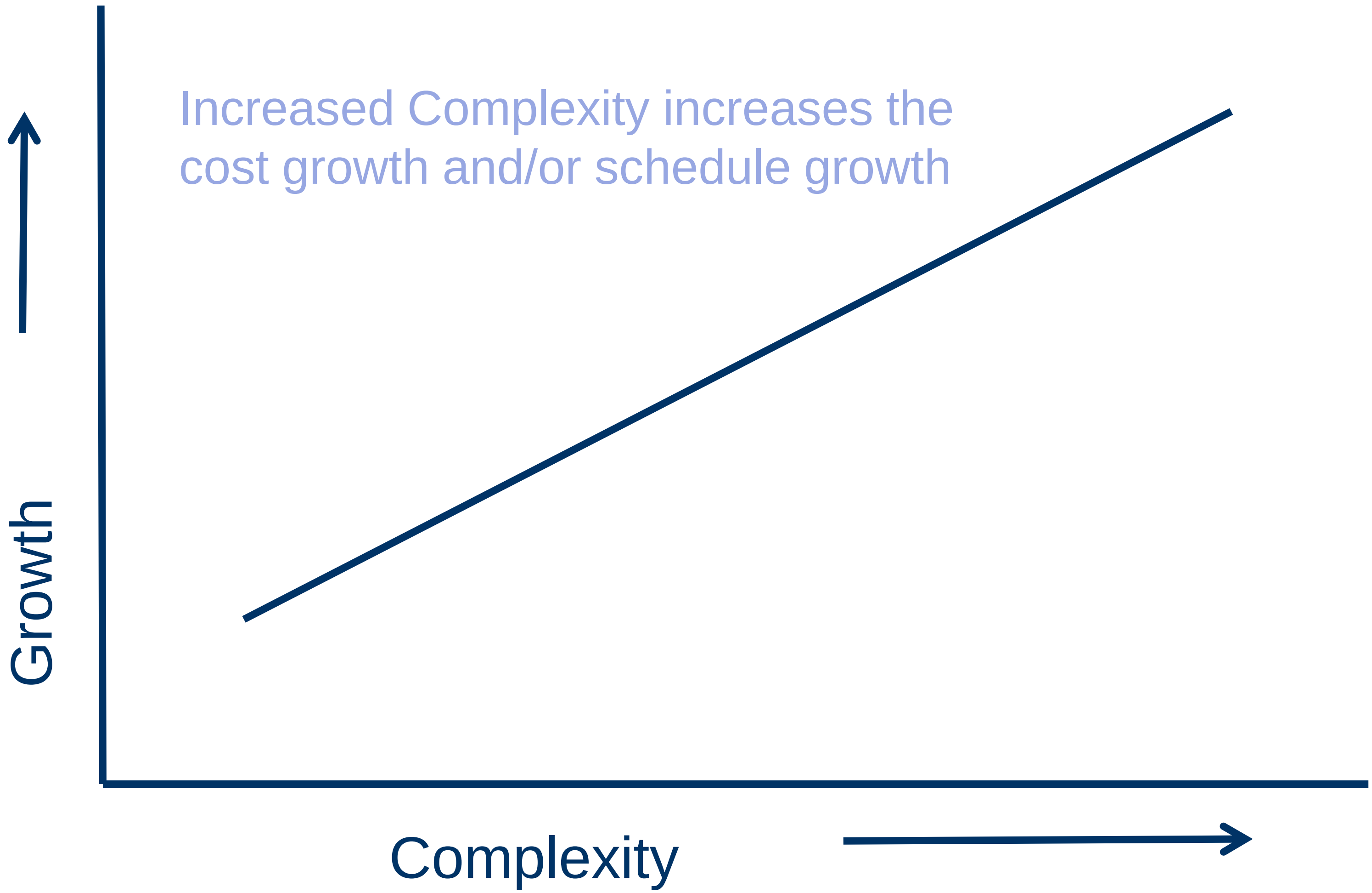
Cost and Schedule Uncertainty Guidelines

Step 2 – Framework Concept

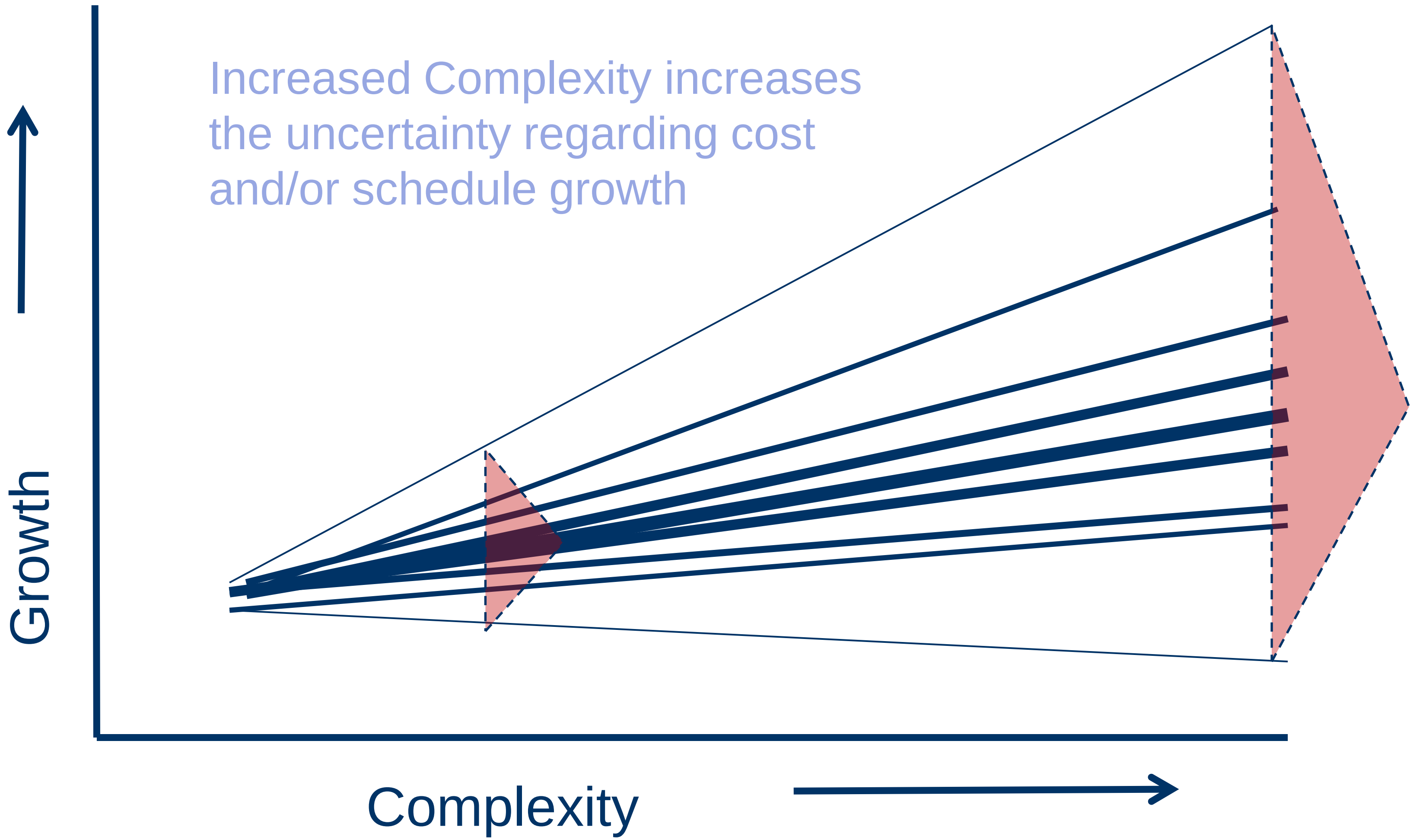
Premise 1 – Uncertainty Decreases with Maturity

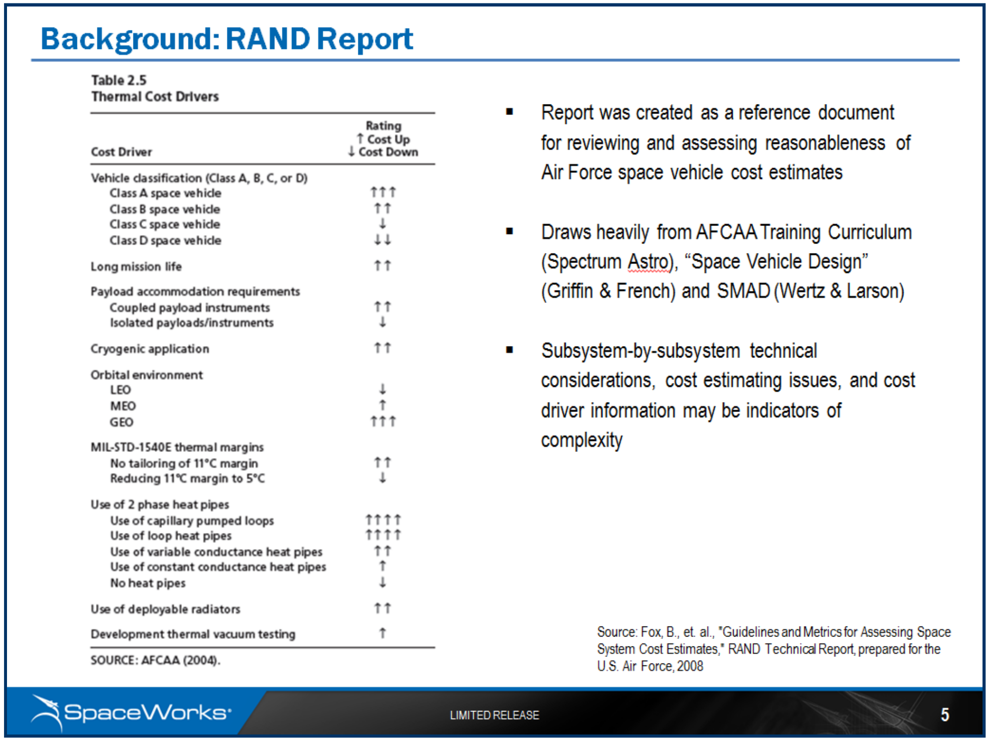


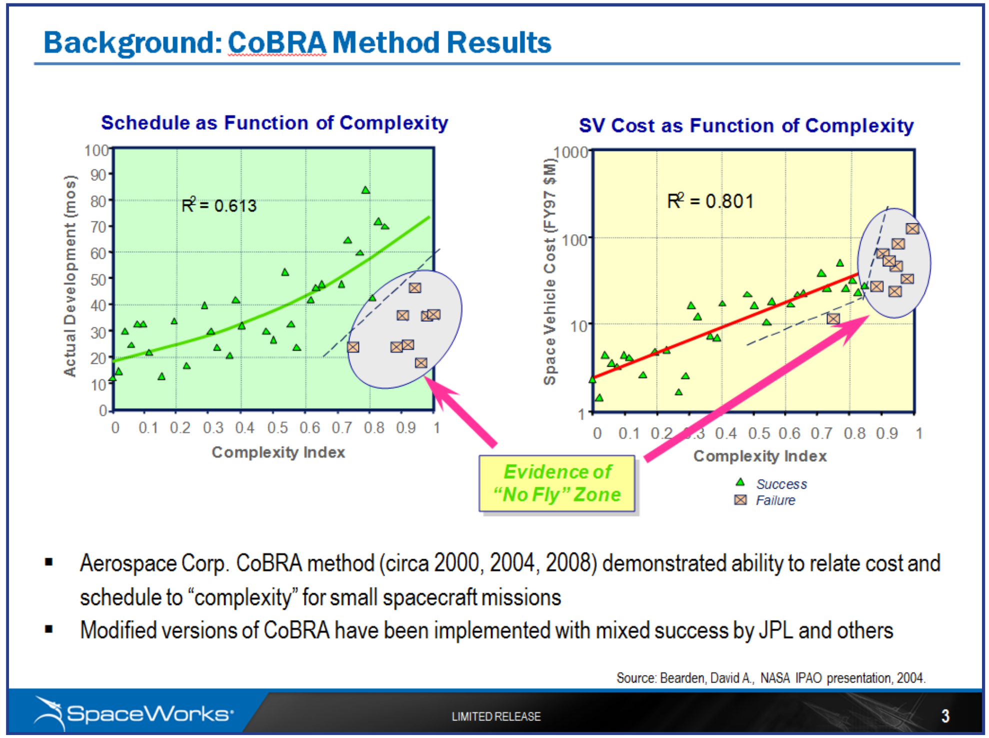
Premise 2 – Increased Complexity has Higher Growth



Premise 3 – Increased Complexity has Higher Uncertainty







Aerospace CoBRA methodology and RAND study identified relationship between cost and technical complexity

- Ability to include both discrete and continuous attributes
- Fairly intuitive process with results traceable to inputs
- Successfully demonstrated for small spacecraft and other spacecraft applications
- RAND study indicated potential subsystem drivers
- CoBRA is a system level model

Pursued path to develop subsystem complexity model

- Derivative of Aerospace Corporation CoBRA methodology
- Approach and attribute selection informed by literature review, SEI SME, Tecolote data findings, and feedback from peer reviews (December 2013, March 2014)
- Complexity scoring at the subsystem level
- Complexity index results based only on attributes available from CADRe's

Factor	Unit	Min	Mean	Max	EXAMPLE	
Total Flight System Cost	(FY02$M)	0.3	67	215		
Payload Cost	(FY02$M)	0.1	27	132		
Carrier/Spacecraft Bus Cost	(FY02$M)	0.2	34	145		
Development Time (actual)	(mos)	10	38	96		
Payload Mass	(kg)	0	76	780	165	89%
Payload Average Power	(W)	0	70	415	110	72%
Payload Peak Power	(W)	13	127	470	138	56%
Payload Data Rate (average)	(Kbps)	0	6557	90500	7000	80%
Number of Instr						
Foreign Partner						
Mission Design						
Spacecraft Bus						
Design Heritage						
Level of Redunc						
Orbit Regime						
BOL Power						
Orbit Average P						
EOL Power						
Solar Array Are						
Solar Cell Type/						
Solar Array Con						
# Deployed Stru						
Battery Type						
Battery Capacit						
Structures Material		Aluminum	Al w/Comp-face, Exotic	Composite	Al	0%
ADCS Type		None, Magnetic	Grav-Grad, 3-axis-(ST)	Dual-mode	Spin	40%
Pointing Accuracy	(deg)	0	2.9	0.0001	1.00	38%
Pointing Knowledge	(deg)	0	1.5	0.00003	0.70	27%
Platform Agility (slew rate)	(deg/sec)	0	0.504	5.000	2.00	95%
Number of Thrusters+Tanks	(#)	0	4	22	16	87%
Propulsion Type		None, Cold-Gas	Mono, Biprop-(blow,pres)	Ion	Mono	40%
Total Impulse (delta-V)	(m/sec)	0	105	1744	1000	90%
Downlink Comm Band		UHF/VHF/SHF	S, L	X, Ka/Ku	S	25%
Max Downlink Data Rate	(kbps)	1	1200	40000	78	32%
Max Uplink Data Rate	(kbps)	0.1	29	1000	0.5	10%
Transmitter Power (peak)	(W)	1	8	60	5	19%
Central Processor Power	(Mips)	1	14	119	10	59%
Flight Software Reuse	(%)	0%	29%	90%	50%	25%
Data Storage Capacity	(Mbytes)	0	629	8000	1000.0	78%
Thermal Type		passive	heaters, semi-active	active, cryo	heaters	25%
Multi-Element System?		single-sc	separated, multiple-sc	entry/landed	single	0%
Mean Complexity Index		4%	37%	63%		50%
Normalized Complexity Index		0%	56%	100%		77%

Source: Bearden, David A., "A Complexity-based Risk Assessment of Low-Cost Planetary Missions: When is a Mission Too Fast and Too Cheap?", Fourth IAA International Conference on Low-Cost Planetary Missions, JHU/APL, Laurel, MD, May 2000.

Guideline Tables

- Developed at specific hardware or work areas, based on data availability
- Meant as a reference point (anchor) for which project specific distributions can be generated
- Flexible to allow updates and expansion with additional data and/or research

		Technical Complexity		
		Low	Medium	High
Design Maturity	CSR/SRR	mean - X_{11} * Estimate std deviation - Y_{11} * Estimate	mean - X_{11} * Estimate std deviation - Y_{11} * Estimate	mean - X_{11} * Estimate std deviation - Y_{11} * Estimate
	PDR	mean - X_{21} * Estimate std deviation - Y_{21} * Estimate	mean - X_{21} * Estimate std deviation - Y_{21} * Estimate	mean - X_{21} * Estimate std deviation - Y_{21} * Estimate
	CDR	mean - X_{31} * Estimate std deviation - Y_{31} * Estimate	mean - X_{31} * Estimate std deviation - Y_{31} * Estimate	mean - X_{31} * Estimate std deviation - Y_{31} * Estimate

- *Maturity aligns with CADRe capture point*
- *<u>Challenge</u> is in defining "complexity"*

Complexity Index Calculation

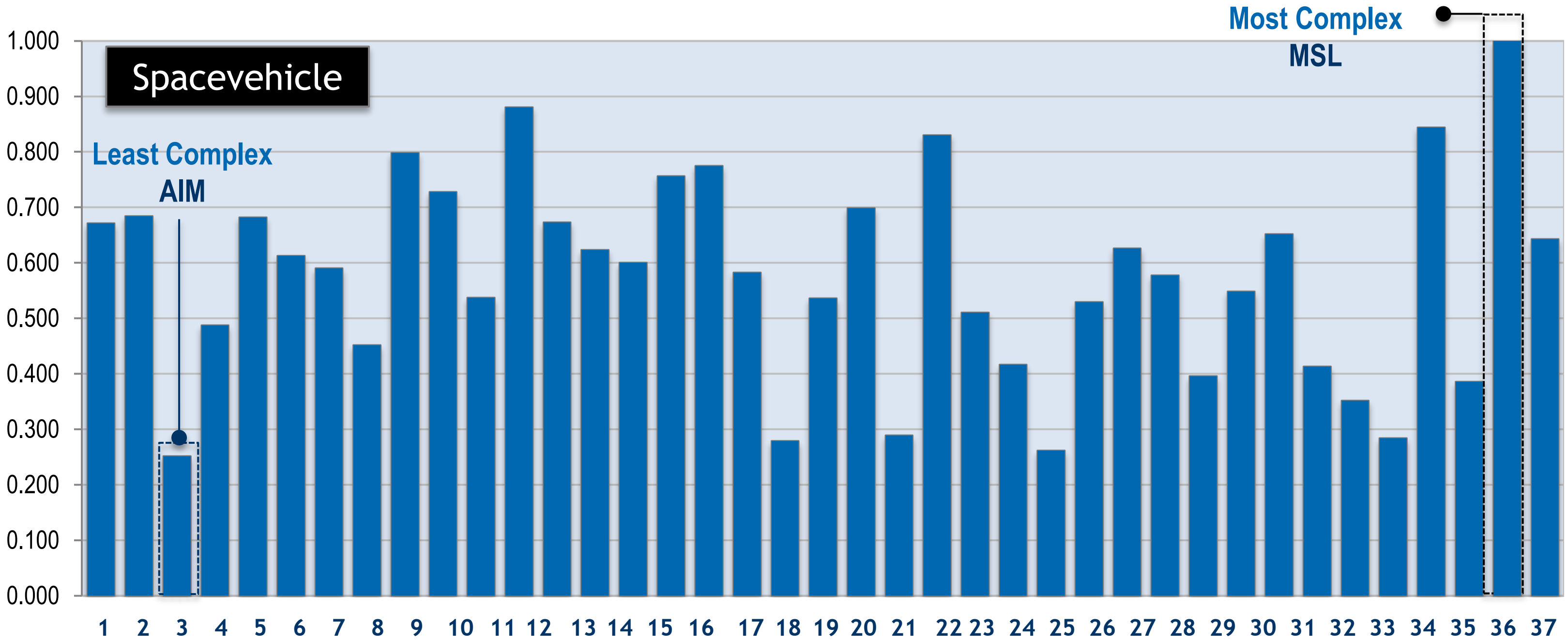
Subsystem (WBS Element)

Attributes (Prog. / Technical)		Attribute Values		Complexity Score Calculation				Cmplx Index
Discrete Attribute	→	Up to 9 Options	→	-100% to +100%	→	Scaled according to significance	→	Normalized Avg of Cmplx Score for all attributes
Continuous Attribute	→	Numerical Value	→	Percent Rank	→			

Subsystem 2 through n

- **System level***
  - Spacecraft heritage
  - Risk/reliability classification
  - Mission life
  - Number of organizations Involved
  - Foreign partnership
  - Number of major spacecraft separations
  - Orbit/destination
- **Structures and Mechanisms**
  - Subsystem heritage
  - Type of materials
  - Subsystem modularity
  - Number of deployments
- **Thermal Control Subsystem**
  - Risk/reliability classification
  - Type of thermal control
  - Mission life
  - Nature of payload accommodations
  - Orbit/destination
- **Guidance Navigation and Control**
  - Pointing accuracy
- **Electrical Power and Distribution**
  - Solar cell type (if applicable)
  - Solar array configuration (if applicable)
  - Battery type (if applicable)
  - Battery capacity (if applicable)
- **Propulsion**
  - Subsystem heritage
  - Propulsion type(s) on spacecraft
  - Number of thrusters + tanks
  - Thrust generated from all propulsion systems
  - Spacecraft land/sample/return
- **Communication**
  - Downlink communication band
  - Maximum downlink data rate
  - Uplink communication band
  - Maximum uplink data rate
- **Command and Data Handling**
  - Subsystem heritage
  - Processor architecture
  - Radiation hardening
  - Data storage available
- **Payload**
  - Number of unique instruments
  - Total mass
  - Average complexity of instruments
  - Payload average power
- **Instruments**
  - Mass
  - Power
  - Instrument type
  - Starting TRL level
  - Heritage
- **Integration and Test**
  - Spacecraft heritage

1 - Messenger
2 - STEREO
3 - AIM
4 - IBEX
5 - LRO
6 - CloudSat
7 - DAWN
8 - GRAIL
9 - JUNO
10 - Kepler
11 - OCO
12 - OSTM
13 - Phoenix
14 - Spitzer
15 - Calipso
16 - MRO
17 - GLAST
18 - AQUA
19 - COBE
20 - CONTOUR
21 - Deep Impact
22 - FAST
23 - GALEX
24 - GENESIS
25 - LANDSAT 7
26 - LCROSS
27 - Mars Pathfinder
28 - NEAR
29 - New Horizons
30 - RHESSI
31 - SAMPEX
32 - Stardust
33 - SWAS
34 - TIMED
35 - TRACE
36 - TRMM
37 - WIRE
38 - MSL
39 - MER



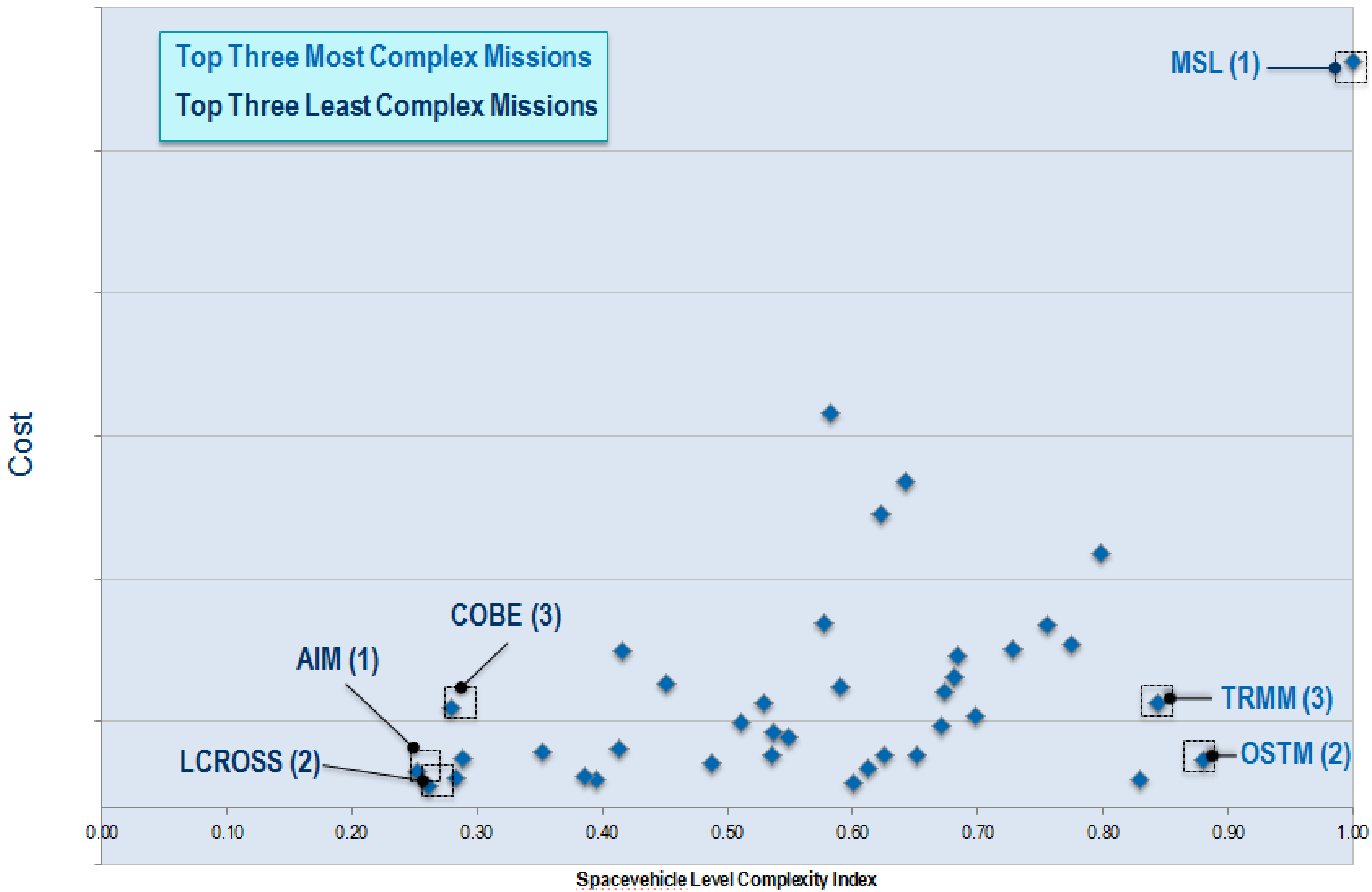
Five (5) Most Complex

- MSL (#36)
- OSTM (#12)
- TRMM (#36)
- GALEX (#23)
- JUNO (#9)

Five (5) Least Complex

- AIM (#3)
- LCROSS (#26)
- COBE (#19)
- TRACE (#35)
- FAST(#22)

Relationship Between Cost and Complexity



Challenges in the Framework

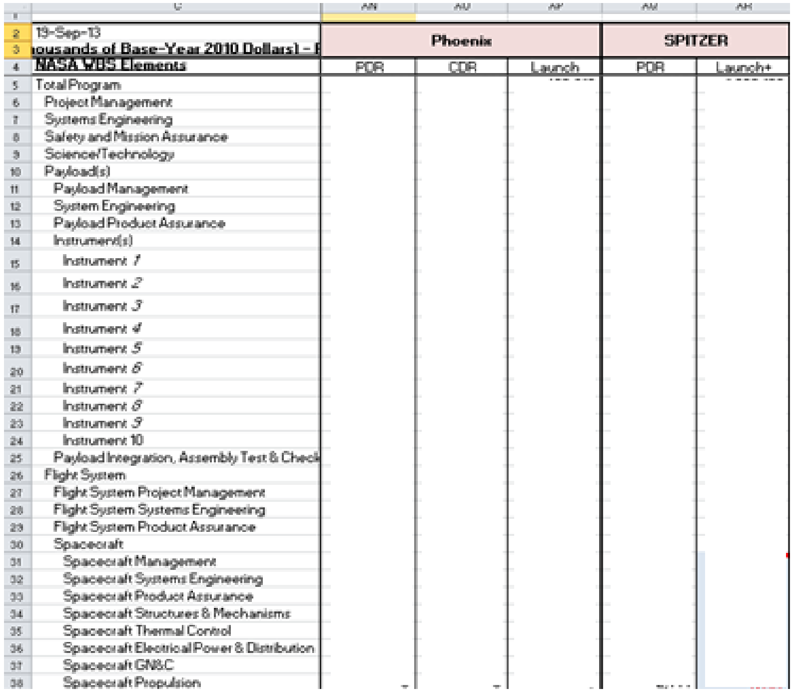
- Attributes limited to data available in CADRe, peer review identified additional potential drivers for consideration
- Some missions lacked all data, so removed from analysis – result is dataset reduced to 37 missions
- Calculations currently based on equi-weighting of attributes, some may need to have a higher weight
- Work in progress – but initial results indicate stratification potential or use to assess uncertainty vs complexity

Cost and Schedule Uncertainty Guidelines

Step 3 – Data Collection

Developed Mapped and Normalized Cost Dataset

- Identified 18 missions having a complete temporal (PDR, CDR, and launch) CADRe dataset
- Mapped time phased data to NASA standard subsystem WBS
- Normalized cost to BY2010$K
- Separated the cost into Phase A, Phase B/C/D, and Phase E



	Phoenix			SPITZER	
19-Sep-13					
ousands of Base-Year 2010 Dollars) – F					
NASA WBS Elements	PDR	CDR	Launch	PDR	Launch+
Total Program					
Project Management					
Systems Engineering					
Safety and Mission Assurance					
Science/Technology					
Payload(s)					
Payload Management					
System Engineering					
Payload Product Assurance					
Instrument(s)					
Instrument 1					
Instrument 2					
Instrument 3					
Instrument 4					
Instrument 5					
Instrument 6					
Instrument 7					
Instrument 8					
Instrument 9					
Instrument 10					
Payload Integration, Assembly Test & Check					
Flight System					
Flight System Project Management					
Flight System Systems Engineering					
Flight System Product Assurance					
Spacecraft					
Spacecraft Management					
Spacecraft Systems Engineering					
Spacecraft Product Assurance					
Spacecraft Structures & Mechanisms					
Spacecraft Thermal Control					
Spacecraft Electrical Power & Distribution					
Spacecraft GN&C					
Spacecraft Propulsion					

- Developed estimate growth factors for each WBS by milestone for Phase B/C/D
  - Launch Final Cost / CDR Estimate = CDR Growth Factor
  - Launch Final Cost / PDR Estimate = PDR Growth Factor

Developed a Normalized Schedule Dataset

- Developed standardized Schedule Collection structure
- Obtained source CADRe schedules for the 18 missions for which temporal cost data was available
- Captured key schedule dates from the source files
- Created 108+ work-day duration metrics by subsystem for 17 of the 18 missions
- Developed duration growth factors for the 108+ metrics

- Dataset enables:
  - Historical duration growth analysis for major work efforts
  - Alignment of cost and schedule metrics for correlation and sensitivity analysis
  - A framework for continued data collection
  - A potential template for a high-level schedule model for us in Phase A or parametric analysis

	Award	PDR	CDR	Obs I&T Start	PSR	Ship	Launch
Space Vehicle							

	Award	PDR	CDR	Subsystem Delivery	S/C I&T Start	S/C Delivery
Spacecraft						
Structures						
Thermal Control						
EPS						
GN&C						
Propulsion						
Communications						
C&DH						
Software						

	Award	CDR	Delivery
Instrument 1			
Instrument 2			
Instrument 3			
.....			
Instrument n			

WBS#		Award	PDR	CDR	Obs I&T Start	PSR	Ship	Launch	Source
1	Space Vehicle	7/7/99	5/24/01	5/22/02	1/7/03	12/6/03	12/9/03	3/10/04	C02_Agenda.pdf Slide 1; C03_Project_Implementation_O

		Award	PDR	CDR	Subsystem Delivery	S/C I&T Start	S/C Delivery	Source	Notes
1.06.04	Spacecraft	12/1/99	5/23/01	5/22/02		11/6/02	12/9/03	C02_Agenda.pdf Slide 1; C03_Project_Implementation_Overview.pd	
1.06.04.04	Structures & Mechanisms Total	5/1/00	4/18/01	3/6/02	10/2/02			C03_Proje	Award date based on 5Month + from S/C Award
1.06.04.05	Thermal Control	5/1/00	[illegible]	10/30/01	7/1/03			C03_Proje	Award date based on 5Month + from S/C Award; PDR dat
1.06.04.06	EPS(Electrical Power & Distribution)	5/1/00	4/19/01	11/2/01	5/26/03			C03_Proje	Award date based on 5Month + from S/C Award
1.06.04.07	GN&C	5/1/00	[illegible]	12/6/01	12/1/03			C03_Proje	Award date based on 5Month + from S/C Award; PDR dat
1.06.04.08	Propulsion	5/1/00	4/19/01	12/14/01	10/23/02			C03_Proje	Award date based on 5Month + from S/C Award
1.06.04.09	Communications	5/1/00	8/2/01	2/26/02	7/1/03			C03_Proje	Award date based on 5Month + from S/C Award
1.06.04.10	C&DH	5/1/00	[illegible]	1/10/02	5/16/03			C03_Proje	Award date based on 5Month + from S/C Award; PDR dat
1.06.04.11	Software	5/1/00	11/9/01	5/5/02	3/28/03			C03_Proje	Award date based on 5Month + from S/C Award

		Award	PDR	CDR	Delivery	Source
1.05.04.01	Instrument 1_MDIS	10/1/99	4/6/01	2/6/02	2/4/03	C03_Project_Implementation_Overview.pdf Slide 5; C08_System_Engineering.pdf Slide 56
1.05.04.02	Instrument 2_GRNS	10/1/99	4/18/01	2/21/02	2/4/03	C03_Project_Implementation_Overview.pdf Slide 5; C08_System_Engineering.pdf Slide 56
1.05.04.03	Instrument 3_MAG	10/1/99	4/5/01	2/8/02	5/21/03	C03_Project_Implementation_Overview.pdf Slide 5; C08_System_Engineering.pdf Slide 56
1.05.04.04	Instrument 4_MLA	10/1/99	4/23/01	2/15/02	2/4/03	C03_Project_Implementation_Overview.pdf Slide 5; C08_System_Engineering.pdf Slide 53
1.05.04.05	Instrument 5_MASCS	10/1/99	4/26/01	2/18/02	2/4/03	C03_Project_Implementation_Overview.pdf Slide 5; C08_System_Engineering.pdf Slide 56
1.05.04.06	Instrument 6_EPPS	10/1/99	4/19/01	2/14/02	2/4/03	C03_Project_Implementation_Overview.pdf Slide 5; C08_System_Engineering.pdf Slide 56
1.05.04.07	Instrument 7_XRS	10/1/99	4/17/01	2/13/02	2/4/03	C03_Project_Implementation_Overview.pdf Slide 5; C08_System_Engineering.pdf Slide 56
1.05.04.08	Instrument 8_DPU	10/1/99	3/29/01	2/4/02	2/4/03	C03_Project_Implementation_Overview.pdf Slide 5

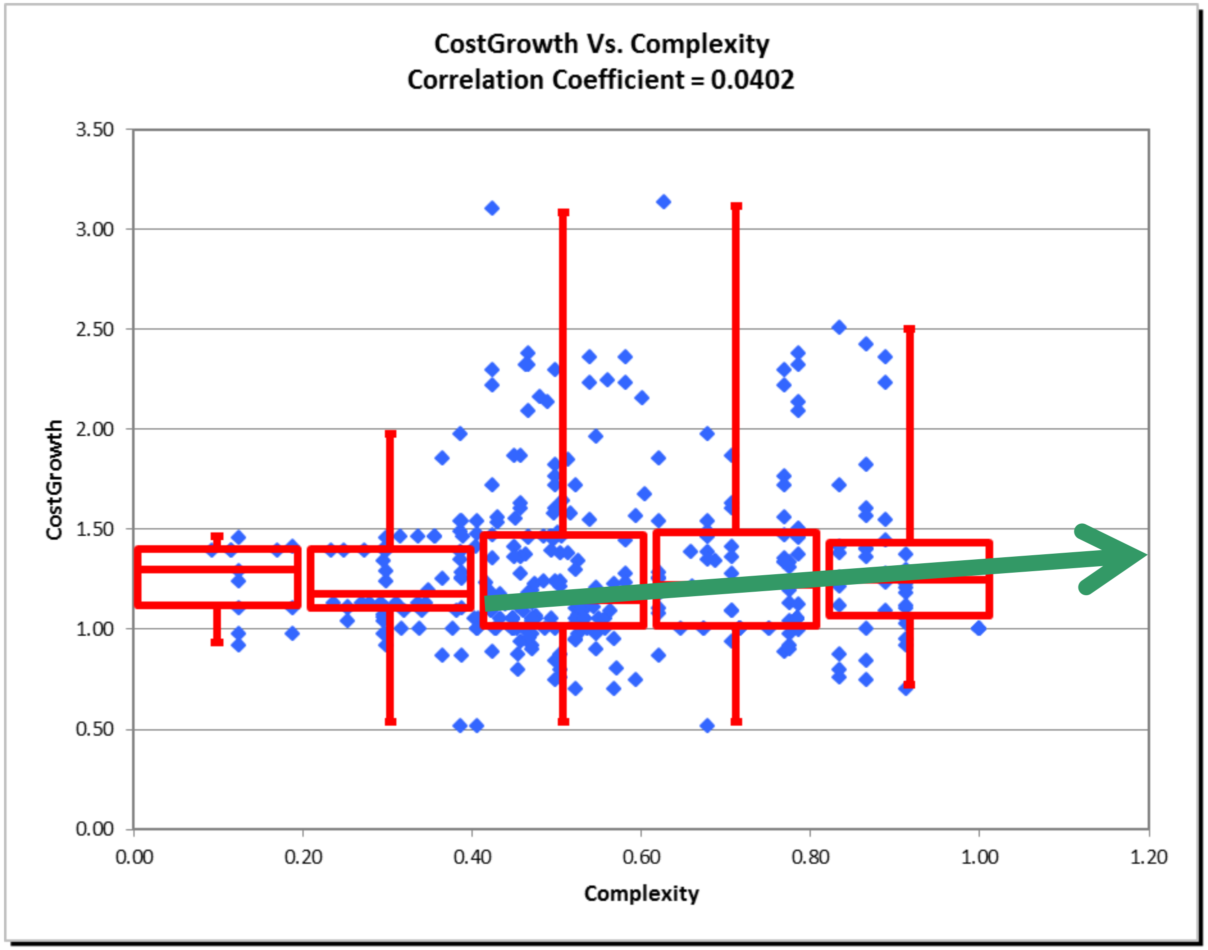
Challenges in Data Collection

- At time of the study, CADRe/ONCE contains raw project data (no normalized dataset) - extensive mapping, allocation, and normalization was required
- Although an extensive amount of missions in CADRe, only a subset (18) had multiple milestones captured
- Detailed schedule data is lacking in CADRe and source documents, additional focus needed to enhance capability to develop appropriate growth metrics
- Although limitations, the resulting dataset was consistent, complete, and useful for growth analysis – continued population of CADRe's will improve dataset and analysis

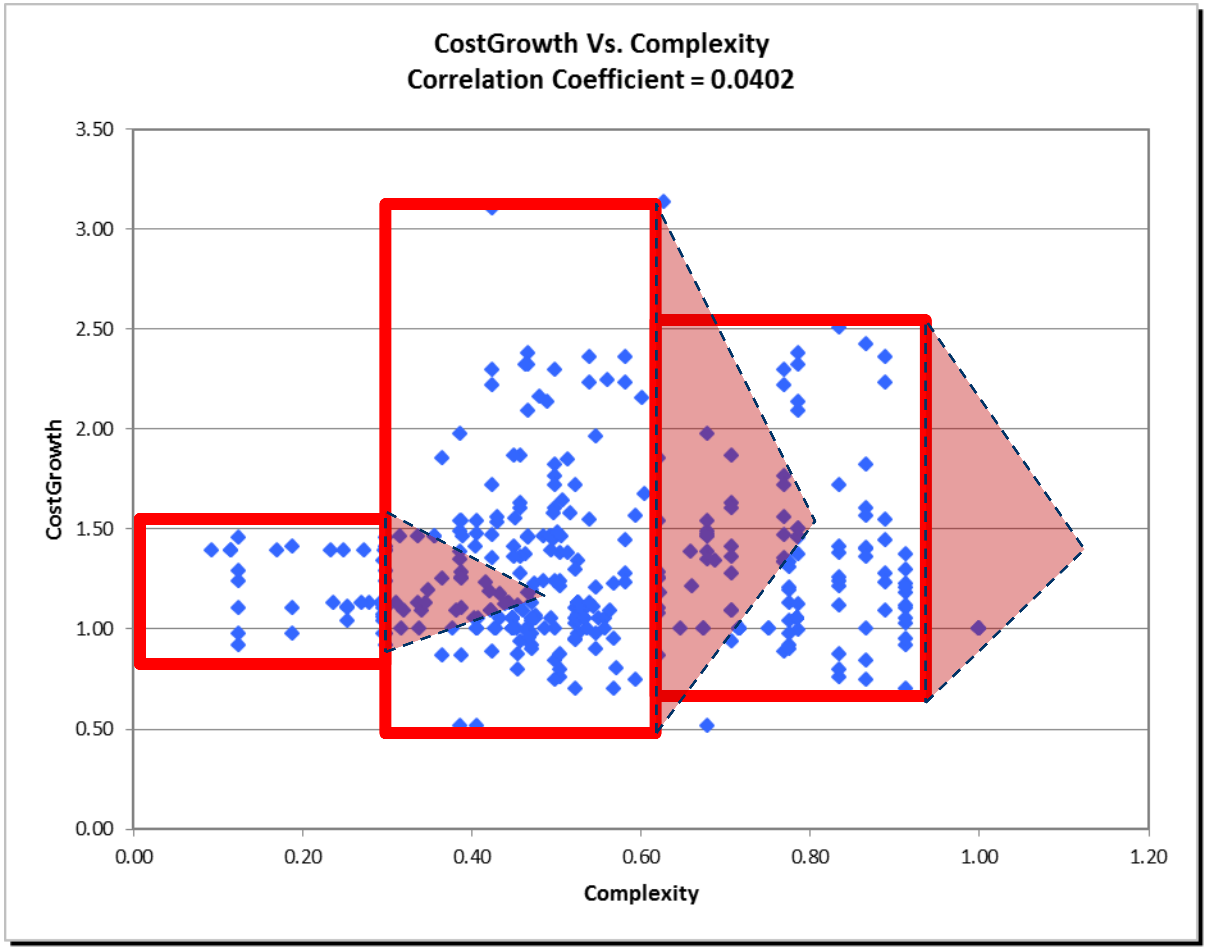
Cost and Schedule Uncertainty Guidelines

Step 4 – Analysis and Stratification

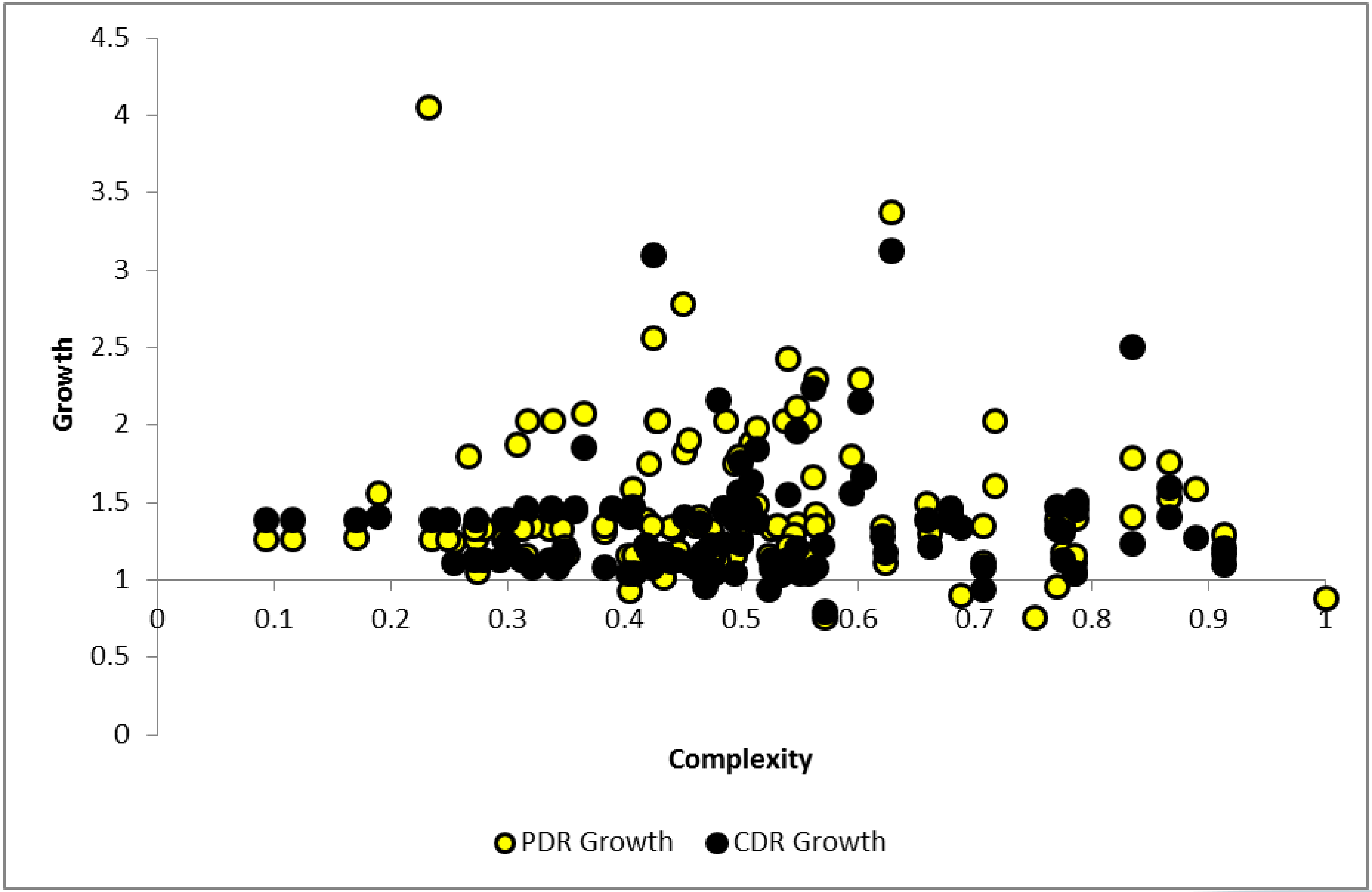
Does Growth Relate to Complexity?



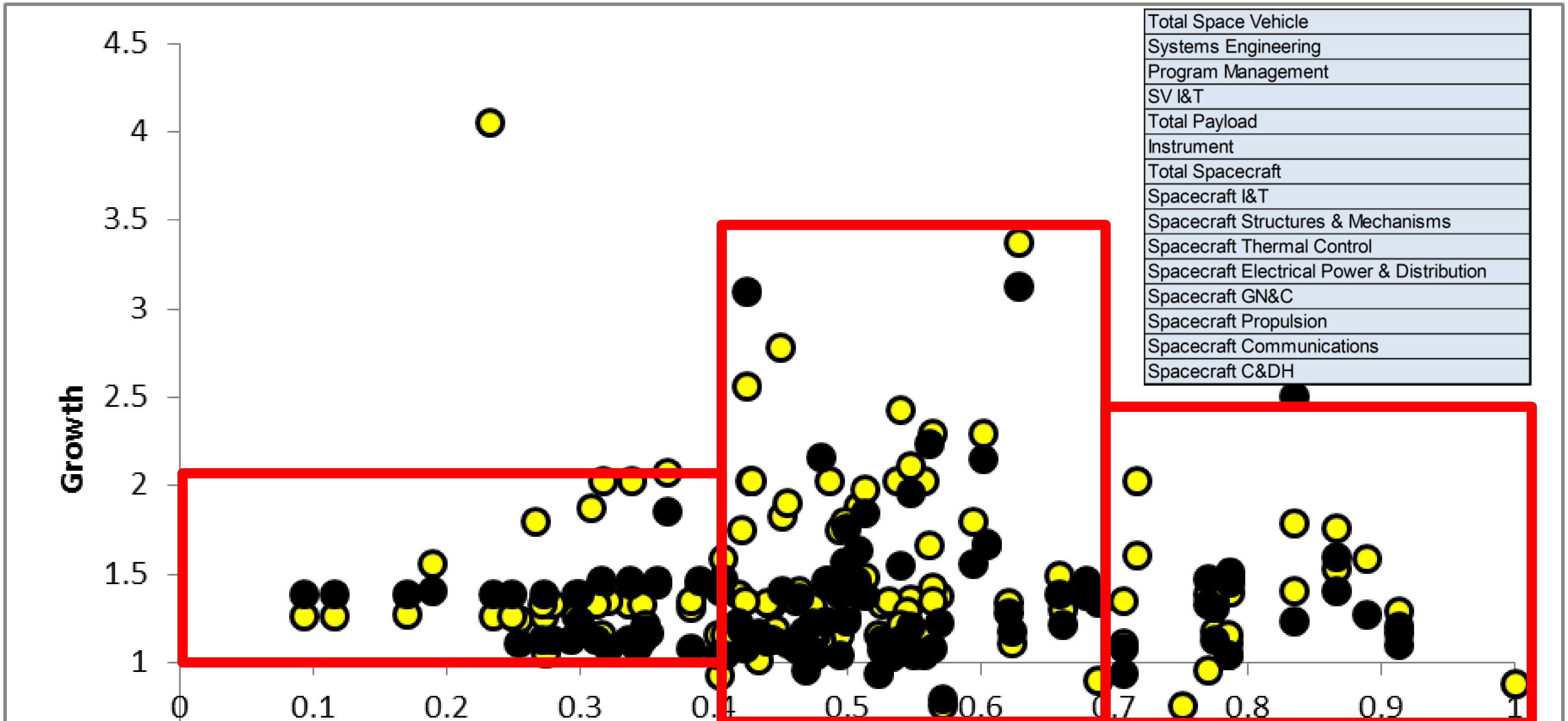
Used Three (3) Complexity Bins (Low, Med, High)



PDR Dispersion Slightly Higher than CDR



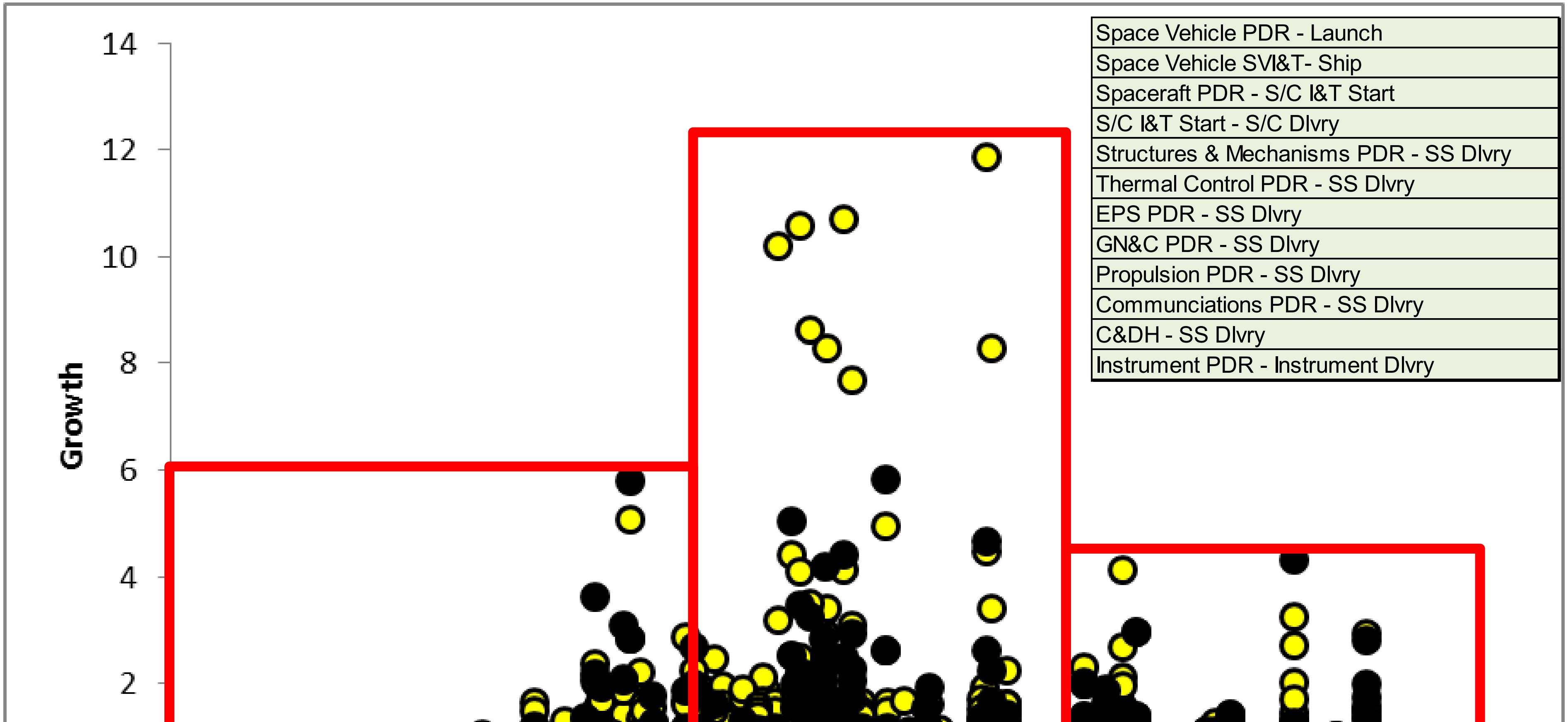
Distributions Determined from Bins
(Low = 0-0.4, Med = 0.4 -0.7, High >0.7)



PDR	Low Complexity	Medium Complexity	High Complexity
Mean	1.409	1.521	1.353
Std Dev	0.254	0.459	0.312
CV	0.18	0.30	0.23

CDR	Low Complexity	Medium Complexity	High Complexity
Mean	1.303	1.372	1.335
Std Dev	0.184	0.435	0.355
CV	0.14	0.32	0.27

Duration Growth – All Subsystems



PDR	Low Complexity	Medium Complexity	High Complexity
Mean	1.250	1.578	1.351
Std Dev	0.564	1.589	0.628
CV	0.45	1.01	0.46

CDR	Low Complexity	Medium Complexity	High Complexity
Mean	1.139	1.213	1.204
Std Dev	0.636	0.672	0.531
CV	0.56	0.55	0.44

Challenges in Data Analysis

- Sample size of 18 missions is small - aggregation of all data points allows for investigation of premise (complexity affects growth range) and to ascertain bins
  - Due to small sample size, some bins for subsystems are non-existent or have very limited data points (1-3)
  - Low complexity bins for some subsystems showed a higher growth and dispersion than the Medium complexity – opposite of expectations
- Many metrics to report for duration, identified a subset for use and publication
- Cost distributions need to be developed for TI and TD (Burn Rate) aspects
- Distributions identified are typically at a level higher than JCL model inputs
- Duration distributions should ideally be at task level, available data is not at that granularity

Cost and Schedule Uncertainty Guidelines

Step 5 – Calibration

Four Areas of Calibration

Determining project specific relevant range

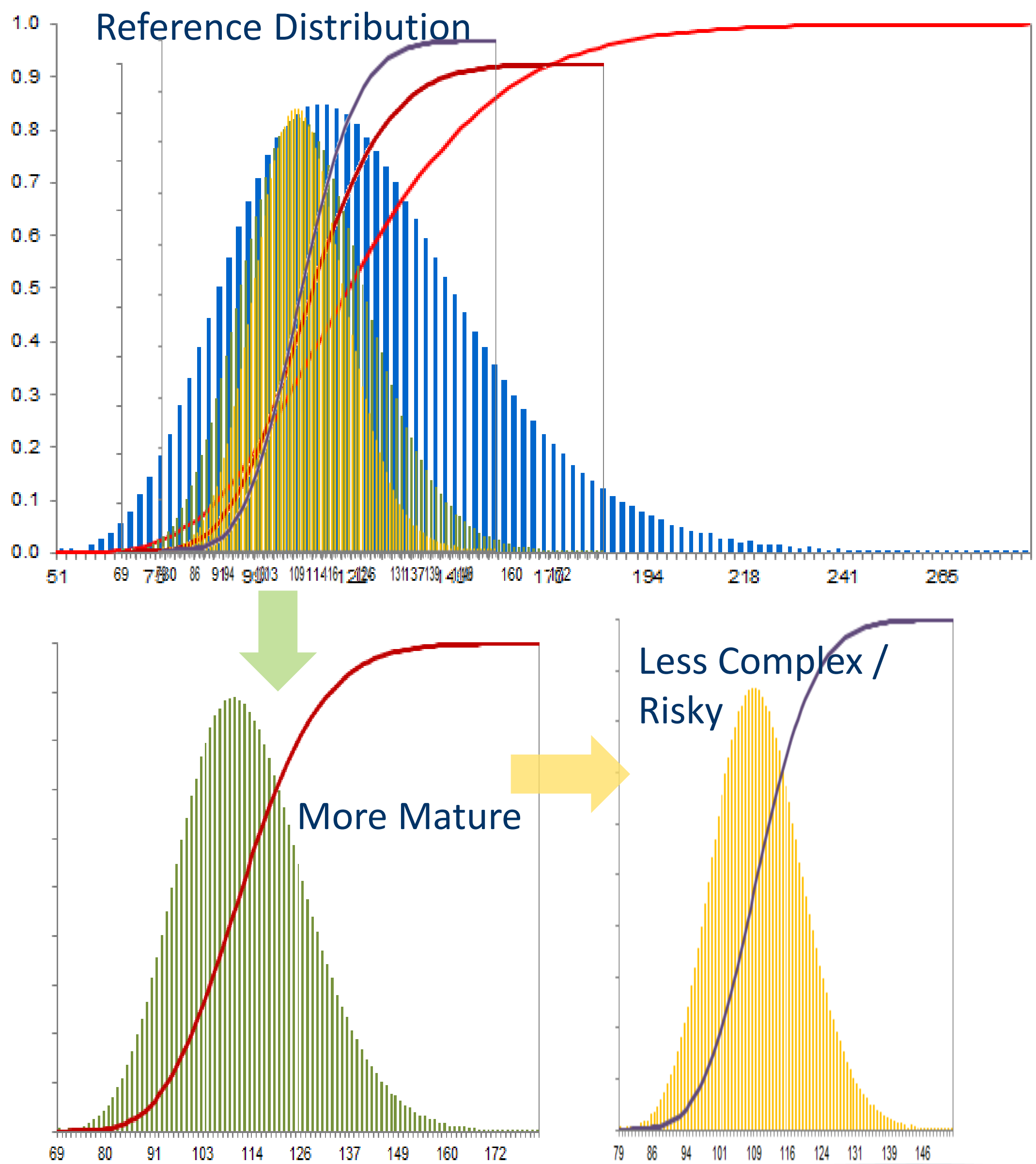
Distributions for TI and TD (Burn Rate)

Derivation of distributions for lower-level of detail

Mechanism for avoiding risk double-count

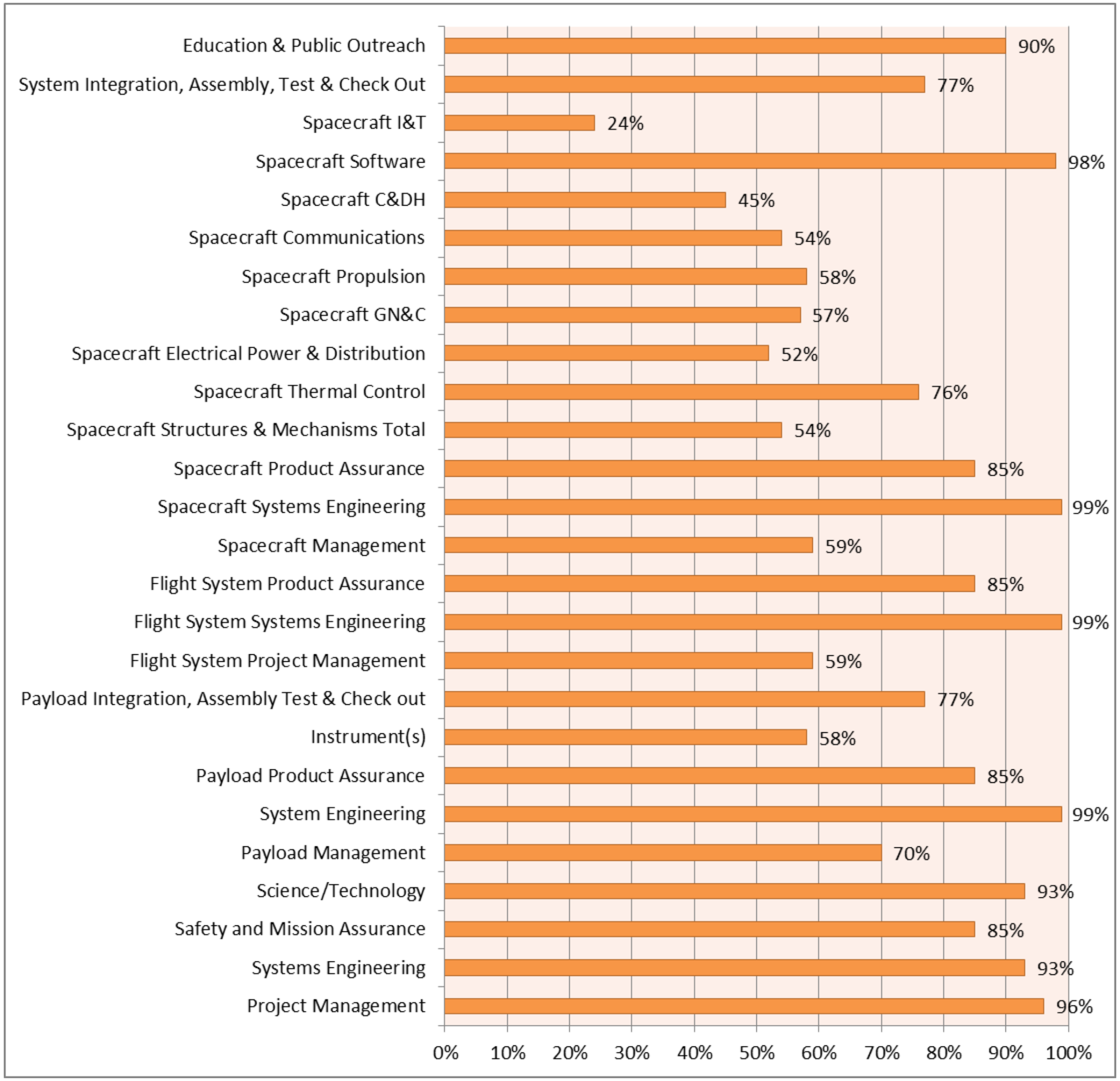
Historical Distributions are Starting Points

- **Growth distributions based on historical projects provide a reference point (starting position)**
- **Through understanding the projects in the dataset, analysts can adjust the distribution**
- **Identification of differences provides rationale for why the historical range is not relevant and enables determination of reasonable distribution for the project**
  - If the project is deemed to more mature - scale both the average growth and dispersion
  - If the project is deemed to be less complex - scale the average growth
  - If the project is deemed to have less risk/uncertainty - scale the dispersion

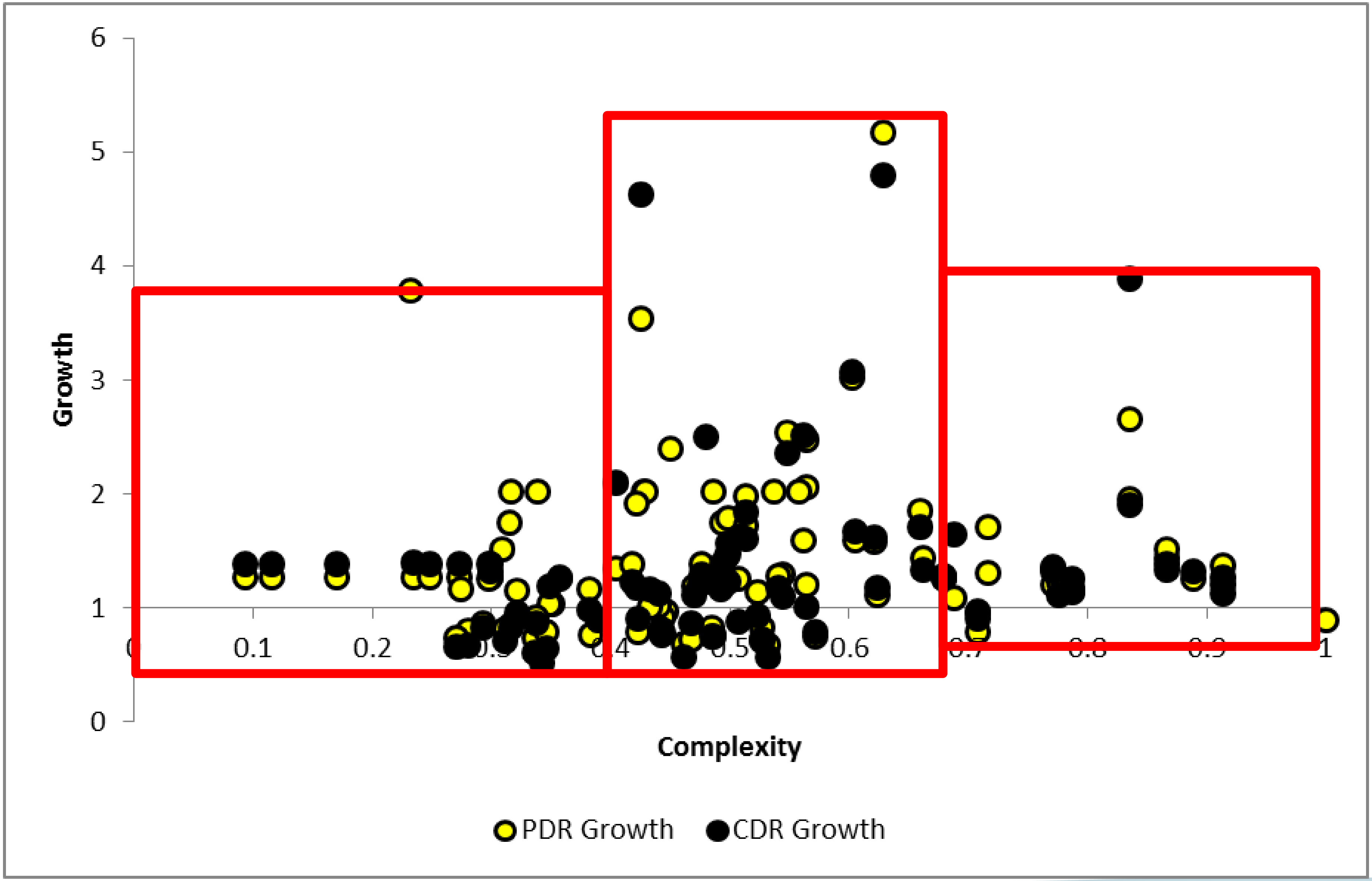


JCL models require TD and TI distributions

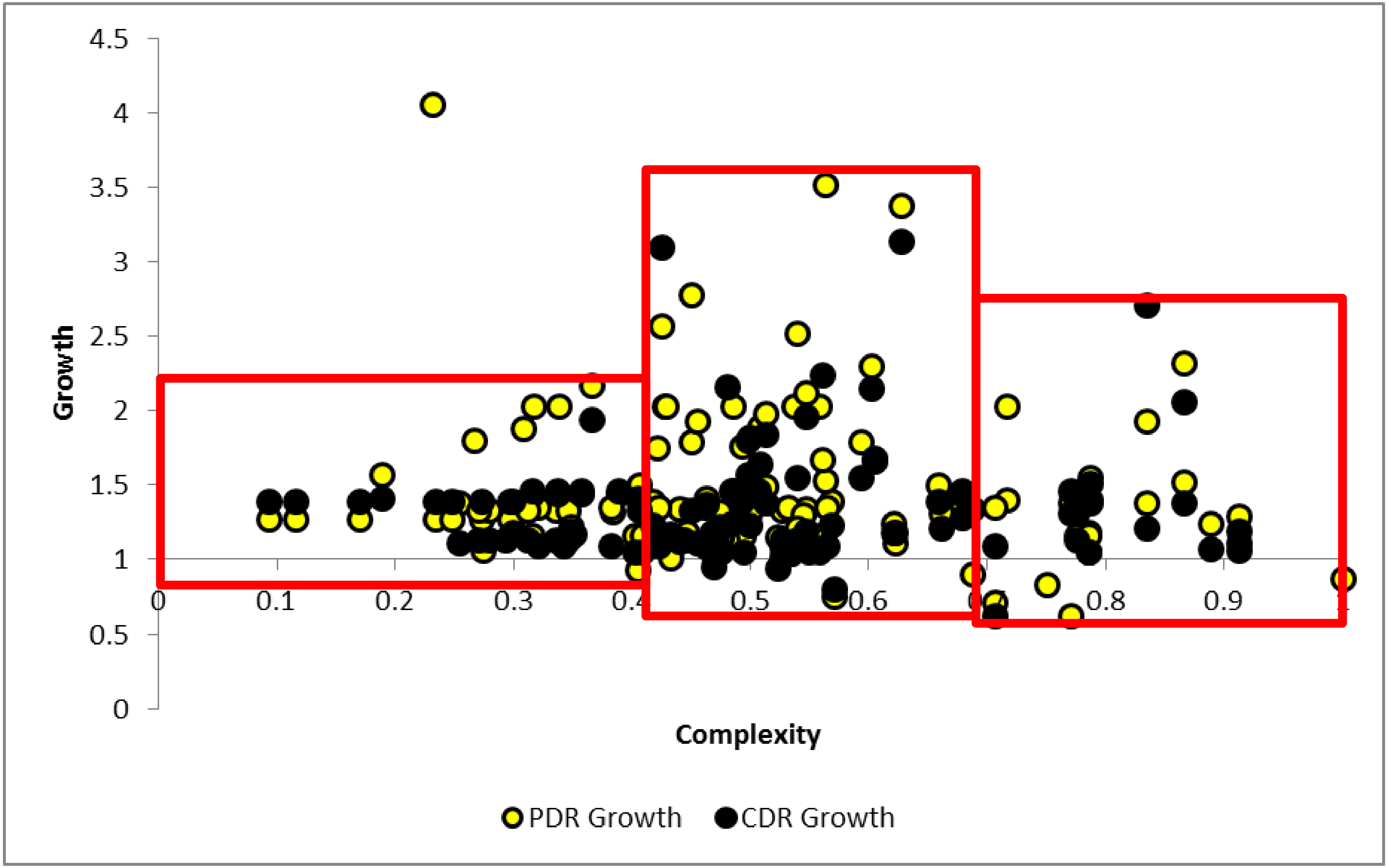
- Total Time Dependent (TD) costs are affected by duration and burn rate
- Objective is to develop historical growth on burn rates
  - Step 1: Determine TD portion of Total Cost
  - Step 2: Divide TD by relevant duration
  - Step 3: Analyze growth
- Analyzed six (6) recent JCL models to identify average TD ratio by subsystem
- Used average TD ratio to break out subsystem cost by phase into TD and TI buckets



TD (Burn Rate) Cost Growth – All Subsystems

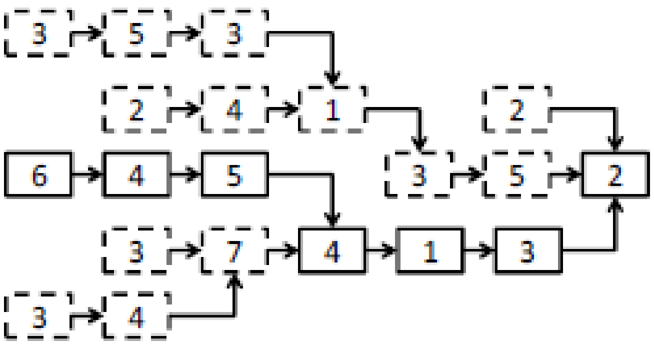


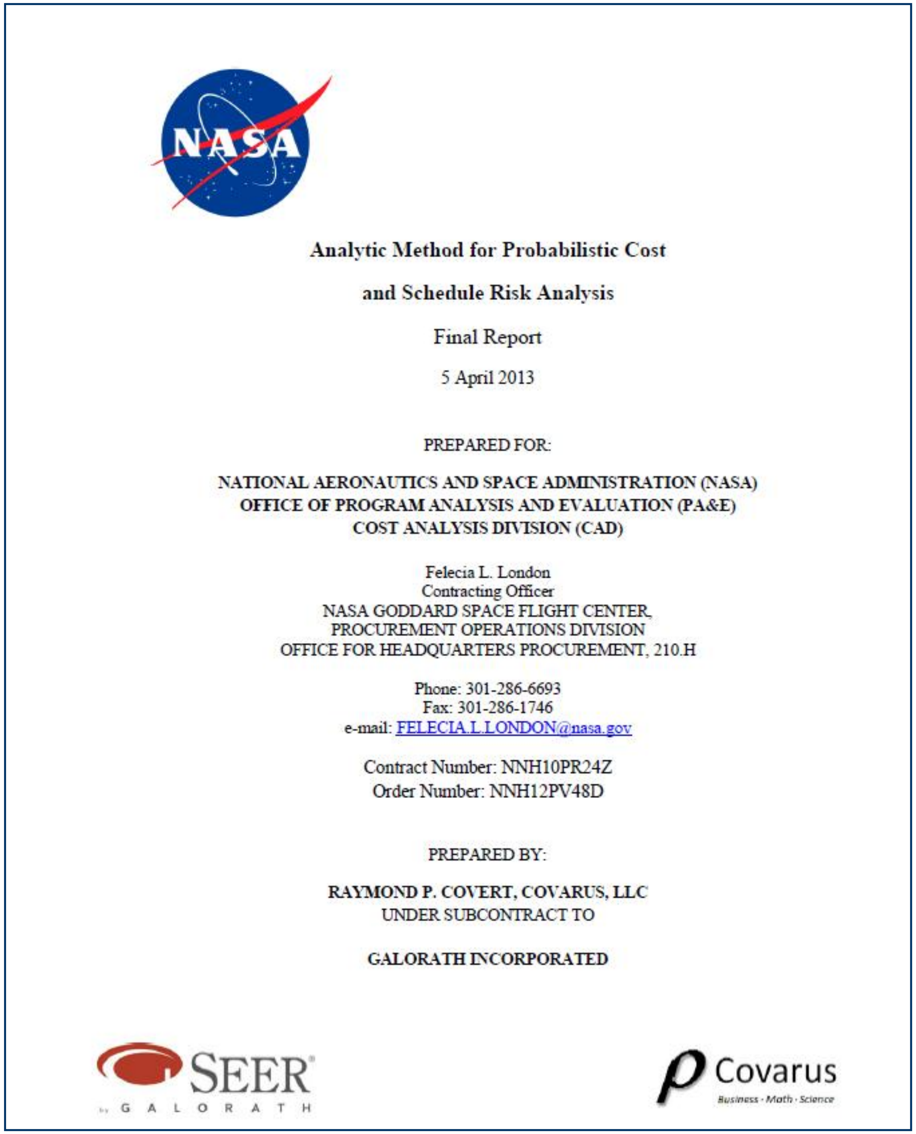
Time Independent (TI) Cost Growth (all subsystems)



Considerations for Lower Level Application

- Schedule models differ from cost models - order versus summation statistics
- In summation models, analytic techniques can be used to derive summation distributions from lower level distributions.
- Conversely, given certain conditions, lower level distributions can be derived from a summary distribution. Note: lower level distributions will be broader than summary
- Reducing the network under a schedule summary to a linear path enables similar methods to apply





Analytic Method for Probabilistic Cost

and Schedule Risk Analysis

Final Report

5 April 2013

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Source: Covert, Ray, "Analytical Method for Probabilistic Cost and Schedule Analysis," NASA CAD Research, April 2013
Source: Book, S.A ,Schedule Risk Analysis: Why it is Important and How to Do It," GASW Workshop 2002, March 2002

The Equation – Solving for Lower Level Distributions to Match Summary Mean and 80% value

- **Basic Formula**

Given a WBS of n elements, X_1, X_2, ... and X_n, the formula to compute the variance of the total is given by

$$\sigma_{Total}^2 = \sum_{i=1}^{n} \sigma_i^2 + 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \rho_{i,j}\, \sigma_i \sigma_j = \boldsymbol{\sigma}' \Sigma\, \boldsymbol{\sigma} \qquad (1)$$

where:

n is the number of WBS elements, which can be any positive integer
σ_{TOTAL} is the standard deviation of the total
σ_i is the standard deviation of the ith element, X_i ($i = 1,\ldots,n$)
$\rho_{i,j}$ is the pairwise correlation between X_i and X_j ($i, j = 1,\ldots,n$)
$\boldsymbol{\sigma}' = (\sigma_1, \sigma_2, \ldots, \sigma_n)$
$\boldsymbol{\Sigma}$ = the correlation matrix of the WBS elements

- **Given an assumed correlation**

If the user specifies a global correlation coefficient for all WBS elements, we can also calculate the respective PEV measure to match the total variance. The formula to calculate the PEV is given below:

$$PEV = \left(\frac{\sigma_{Total}^2}{\sum_{i=1}^{n} p_i^2 + (\rho_G)\, \mathbf{P}'(\mathbf{E} - \mathbf{I})\, \mathbf{P}} \right)^{0.5} = \left(\frac{\sigma_{Total}^2}{\sum_{i=1}^{n} p_i^2 + 2(\rho_G) \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} p_i p_j} \right)^{0.5} \qquad (3)$$

where:

p_i is the point estimate of the ith element, X_i ($i = 1,\ldots,n$)
$\mathbf{P}' = (p_1, p_2, \ldots, p_n)$
ρ_G is the user-specified global pairwise correlation between X_i and X_j ($i, j = 1,\ldots,n$)

Using the PEV from Equation 3 and the user-specified correlation coefficient, the standard deviation at the total level will match the target number.

Calculating the Resulting Log-Normal Distributions

Log-Normal Distribution. Since the distribution at the total level is most likely log-normal, we applied the log-normal distribution to approximate the individual WBS elements. Given the unit-space mean (Mean) and standard deviation (Stdev), its log-space mean (μ_L) and standard deviation (σ_L) are derived as follows:

$$\sigma_L = \sqrt{\ln\left(1 + (Stdev / Mean)^2\right)} = \sqrt{\ln\left(1 + CV^2\right)} \quad (4)$$

$$\mu_L = \ln(\text{Mean}) - (\sigma_L)^2/2 \quad (5)$$

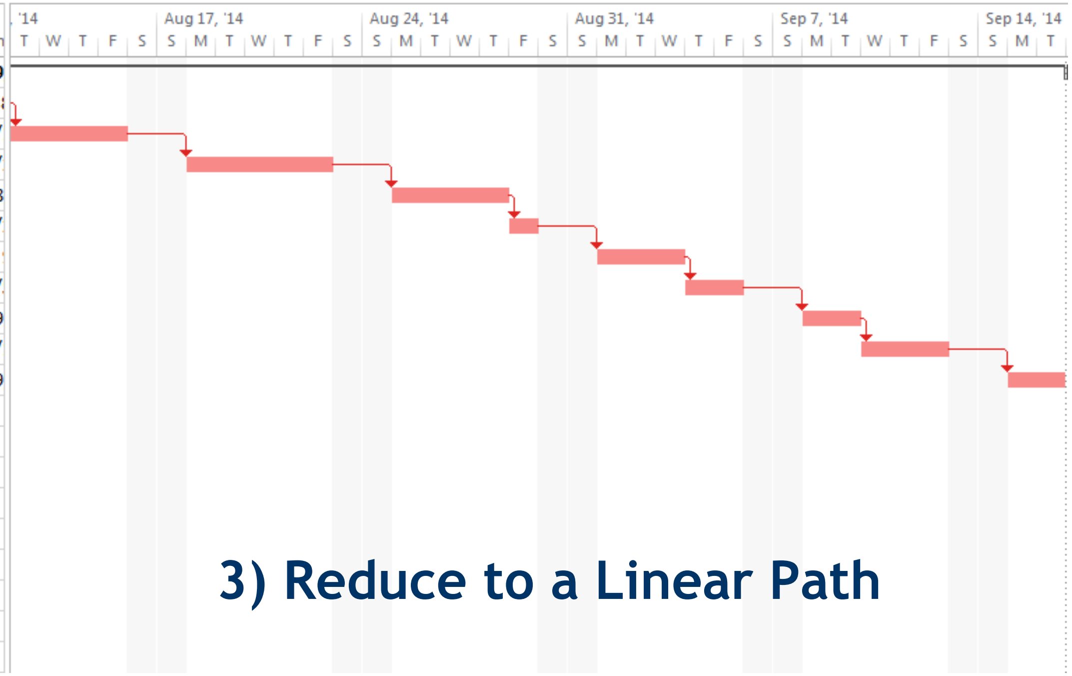
Consequently, its 80th percentile is given by

$$80^{th} = \exp(\mu_L + \text{NormsInv}(0.8)*(\sigma_L)) = \text{LogInv}(0.8, \mu_L, \sigma_L) \quad (6)$$

We used Equations 4 and 5 to generate the log-normal distributions for the individual WBS elements and we used Equation 6 to estimate the 80th percentile for the total.

Summary Distribution Allocation Process
(Reducing to a Linear Path)

Task Name	Duration	Total Slack	Start	Finish
Summary	**32 days**	**0 days**	**Mon 8/4/14**	**Tue 9**
Task 7	6 days	0 days	Mon 8/4/14	Mon 8
Task 8	4 days	0 days	Tue 8/12/14	Fri 8/
Task 9	5 days	0 days	Mon 8/18/14	Fri 8/
Task 14	4 days	0 days	Mon 8/25/14	Thu 8
Task 15	1 day	0 days	Fri 8/29/14	Fri 8/
Task 16	3 days	0 days	Mon 9/1/14	Wed
Task 20	2 days	0 days	Thu 9/4/14	Fri 9/
Task 21	2 days	0 days	Mon 9/8/14	Tue 9
Task 23	3 days	0 days	Wed 9/10/14	Fri 9/
Task 24	2 days	0 days	Mon 9/15/14	Tue 9



3) Reduce to a Linear Path

Summary Distribution Allocation Process
(Calculating Lower Level Distributions)

Task 7	6.0
Task 8	4.0
Task 9	5.0
Task 14	4.0
Task 15	1.0
Task 16	3.0
Task 20	2.0
Task 21	2.0
Task 23	3.0
Task 24	2.0

1 – enter durations

PE	Mean Growth	Std Dev % (PEV = SD/PE)
32	25%	20%

2 – specify summary statistics

Given Correl:	0.60
Calc_PEV:	24.84%

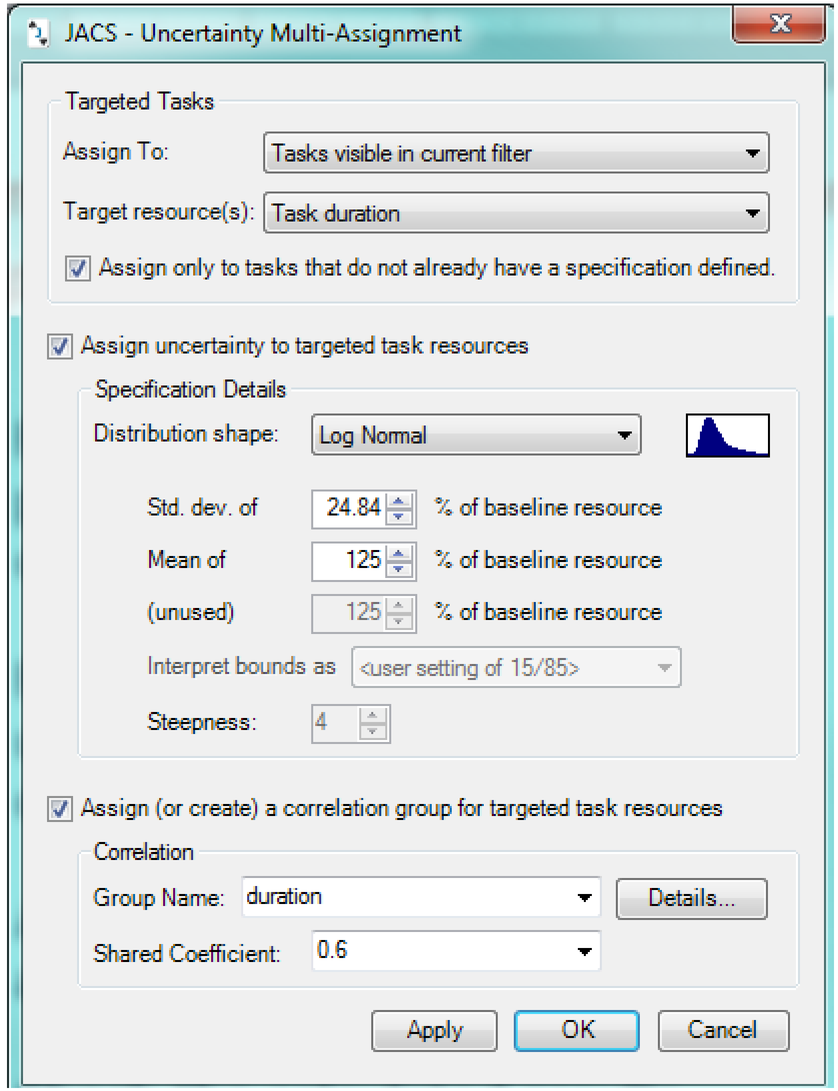
3 – specify correlation and calculate PEV

	mean mxplr	PEV (StdDev%)
Task 7	125.00%	24.84%
Task 8	125.00%	24.84%
Task 9	125.00%	24.84%
Task 14	125.00%	24.84%
Task 15	125.00%	24.84%
Task 16	125.00%	24.84%
Task 20	125.00%	24.84%
Task 21	125.00%	24.84%
Task 23	125.00%	24.84%
Task 24	125.00%	24.84%

4 – determine distributions

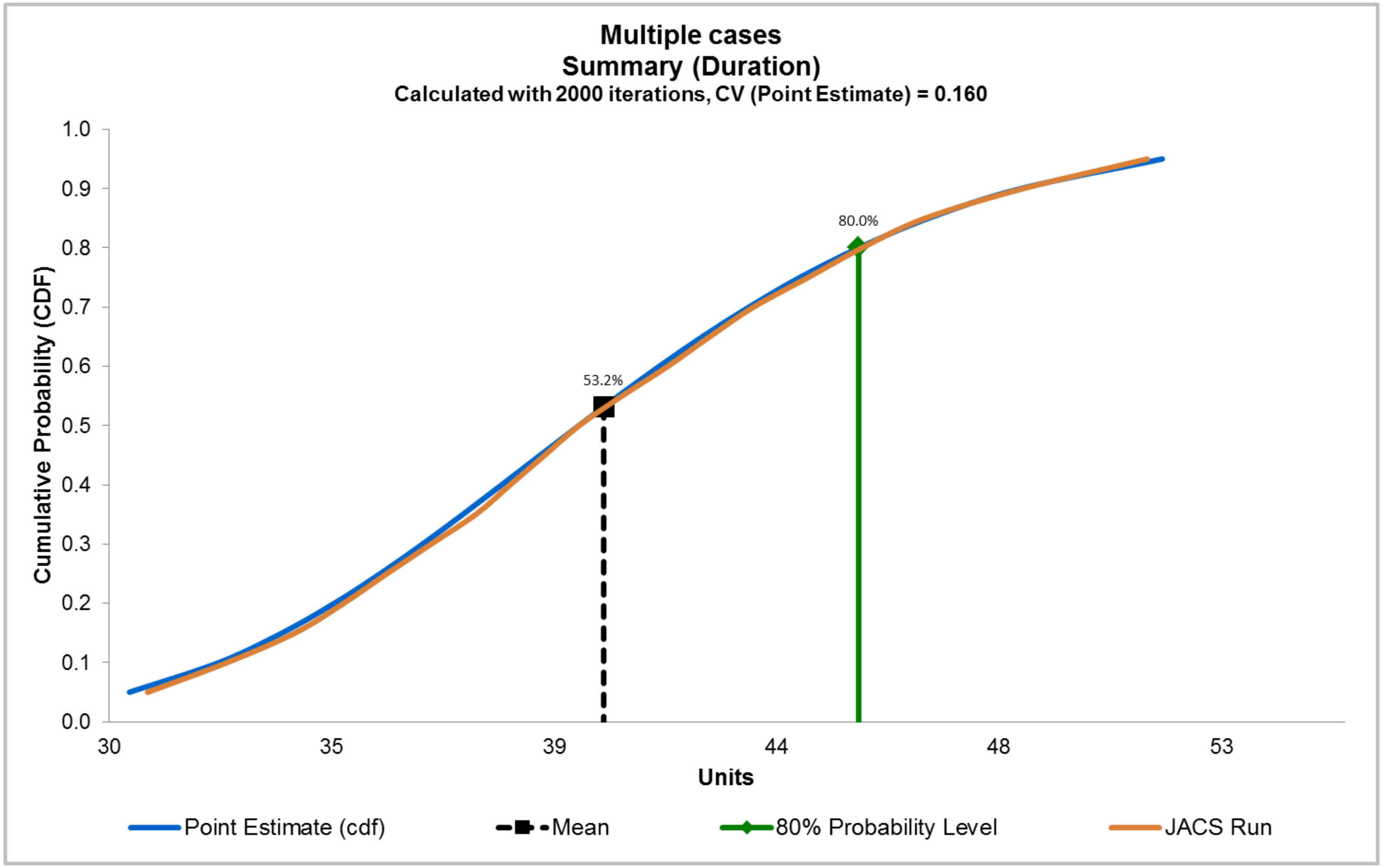
Summary Distribution Allocation Process *(Implementing Distributions)*

- For tasks on the identified path, use the calculated distributions
- For tasks not on the path, use the summary distribution with the mean growth slightly lower
- Apply the correlation assumption



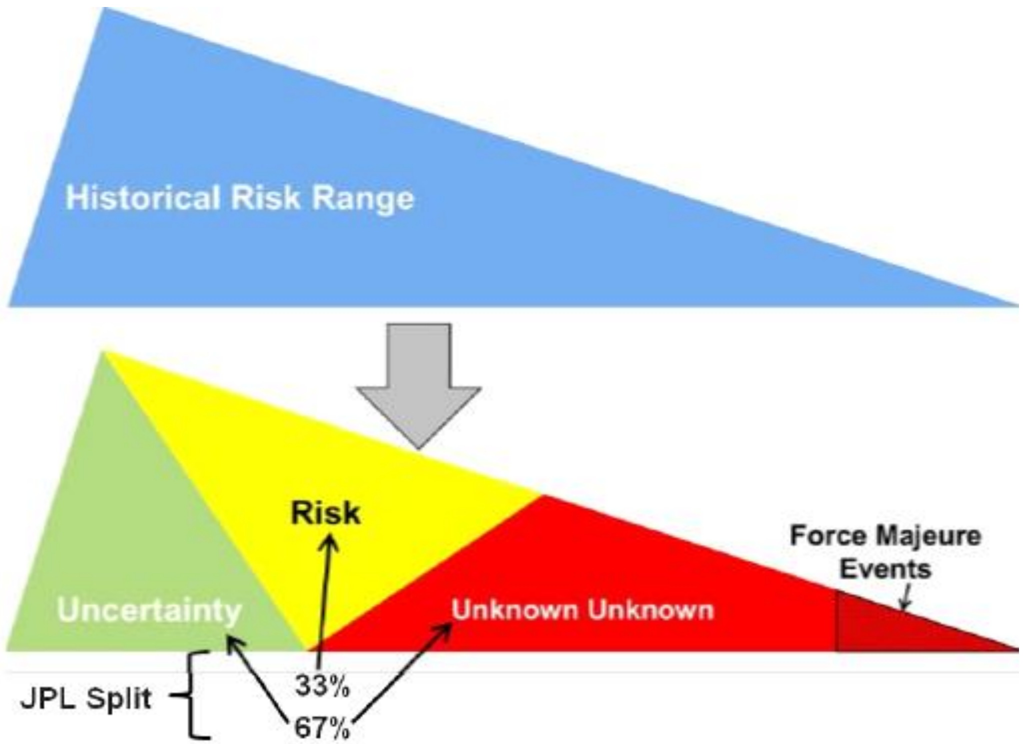
Summary Distribution Allocation Process *(Verifying Result)*

- **Compare calculated distribution versus target for mean and 80%**



Avoiding Double-Counting for Risks *(Background)*

- Use of historical data, implies the capture of typical risks affecting past projects
- Best practice implies understanding the risks inherent in the dataset, and modeling only the additional risks
- Recent studies by NASA HQ has identified challenges in identifying the specific risk events that have occurred on historical projects
- Is there a middle road?
  - Can projects include all identified risks to ensure the nuances of their occurrence ripples into their project plans?
  - Can the reference distribution be adjusted to account for a subset of risks that are deemed to be in the historical data?



Source: Butts, Glenn, “Uncertainty Approach, “ NASA Cost Symposium 2013, August 2013

Adjusting Reference Distribution
(Process)

Implement all risks into a JCL Model

Identify which risks are considered be included in the dataset (double-count risks)

Run the model with uncertainty off and only the double-count risks activated

Obtain cost and schedule statistics (point estimate, mean, standard deviation) for the appropriate summaries

Calculate an adjusted reference distribution by determining the distribution needed to combine with double-count risks to replicate the original reference

Avoiding Double-Counting for Risks
(Calculation)

- **Identify Reference Distribution, for example**
  - Estimate = 100
  - Mean growth = 30%; mean = 130
  - Std Dev = 25%; std Dev = 25
- **Calculate statistics for model with double-count risks and no uncertainty, for example**
  - Estimate = 100
  - Mean growth = 10%; mean = 110
  - Std Dev % of PE = 5%; std Dev = 5
- **Solve adjusted reference distribution**
  - Adjusted Mean = reference mean – mean of double-count risk
    - 130 – 110 = 120; 20% mean growth
  - Adjusted Std Dev % of PE (PEV) = Adj Std Dev / PE = ((reference SD ^2) – (double count SD^2)) ^(0.5)) / pt estimate
    - Adjusted Std Dev = (((25^2)-(5^2))^0.5);
    - = ((625-25)^0.5) 0;
    - = (600^0.5)/100 ;
    - = 24.4949; PEV = 24.4949%

WBS/CES Description	Point Estimate	Mean	Std Dev	80%
Target Total (Reference Distribution)	$ 15,300.000 (12%)	**$19,889.85**	$3,824.82	**$23,189.04**
JCL Model	$ 15,300.000 (12%)	**$19,889.97**	$3,770.53	**$23,169.59**
Adjusted Reference	$ 15,300.000 (21%)	$18,431.93	$3,673.86	$21,592.15
Discrete Risks -Doublecount	$0.00	$1,458.05	$850.25	$2,255.89
Risk 1	$0.00	$162.22	$346.75	$858.84
Risk 2	$0.00	$16.73	$35.98	$82.33
Risk 3	$0.00	$3.62	$7.91	$15.81
Risk 4	$0.00	$5.05	$11.35	$19.42
Risk 5	$0.00	$101.36	$139.36	$258.20
Risk 6	$0.00	$48.50	$109.42	$190.33
Risk 7	$0.00	$341.23	$436.71	$900.55
Risk 8	$0.00	$16.77	$36.07	$82.78
Risk 9	$0.00	$3.55	$7.78	$15.37
Risk 10	$0.00	$5.04	$11.33	$19.94
Risk 11	$0.00	$168.23	$145.42	$314.17
Risk 12	$0.00	$161.99	$346.29	$855.97
Risk 13	$0.00	$4.73	$20.75	
Risk 14	$0.00	$1.01	$4.50	
Risk 15	$0.00	$5.17	$11.61	$20.19
Risk 16	$0.00	$161.73	$345.74	$855.02
Risk 17	$0.00	$16.68	$35.88	$82.58
Risk 18	$0.00	$3.66	$8.00	$16.11
Risk 19	$0.00	$4.95	$11.11	$19.16
Risk 20	$0.00	$161.90	$346.07	$857.74
Risk 21	$0.00	$4.72	$20.73	
Risk 22	$0.00	$1.04	$4.62	
Risk 23	$0.00	$10.91	$14.83	$28.41
Risk 24	$0.00	$35.29	$45.54	$92.49
Risk 25	$0.00	$0.98	$4.38	
Risk 26	$0.00	$10.99	$14.98	$28.65

Challenges in Calibration

- Application in JCL models requires specification of TD and TI uncertainty distributions, improvement in data collection in CADRe's to provide visibility at subsystem will improve overall quality of results for these parameters
- Technique for allocating summary to details requires several major assumptions
  - The identified critical path is the major critical path for all simulation runs
  - All risks on the critical path have the same risk posture
  - Technique ignores impact from links external to the summary
- Obtaining data on actual task level variance grouped by duration length and effort phase (design, fabrication, test, etc) and WBS will provide enhanced duration metrics
- Removal of double-count risk requires indication of what risks historically affect projects, improvement in data collection to categorize and identify risk resolution on past projects will improve capability in the field.

JCL Uncertainty

Next Steps

In Conclusion…

Guidance

- NASA has enough information to make informed uncertainty decisions – the data is there!
- Definitive guidance will be difficult to produce for inputs
- Data does allow for general guidelines for cross-checks

Data

- Data collection has come along way in the last 10 years
- There are still many areas to improve upon
  - Activity level task duration actuals
  - Consistent CBS between projects
  - TD and TI breakouts
  - Correlation assumptions

Capability

- **Product is a work in process**
  - Additional work on all areas (complexity generation, data fidelity, data analysis/trends, etc)

Forward Plan

- **Data will be made available to community (ONCE) in September time frame**
- **There are other techniques* to tackle this problem that need to be incorporated in the uncertainty "portfolio"**

*Several examples are being presented at this Symposium!

Acknowledgements

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