Probabilistic Mass Growth Uncertainties

Eric Plumer, NASA HQ

Darren Elliott, Tecolote Research Inc

Abstract

Mass has been widely used as a variable input parameter for Cost Estimating Relationships (CER) for space systems. As these space systems progress from early concept studies and drawing boards to the launch pad, their masses tend to grow substantially hence adversely affecting a primary input to most modeling CERs. Modeling and predicting mass uncertainty, based on historical and analogous data, is therefore critical and is an integral part of modeling cost risk.

This paper presents the results of a NASA on-going effort to publish mass growth datasheet for adjusting single-point Technical Baseline Estimates (TBE) of masses of space instruments as well as spacecraft, for both earth orbiting and deep space missions at various stages of a project's lifecycle This paper will also discusses the long term strategy of NASA Headquarters in publishing similar results, using a variety of cost driving metrics, on an annual bases. This paper provides quantitative results that show decreasing mass growth uncertainties as mass estimate maturity increases. This paper's analysis is based on historical data obtained from the NASA Cost Analysis Data Requirements (CADRe) database.

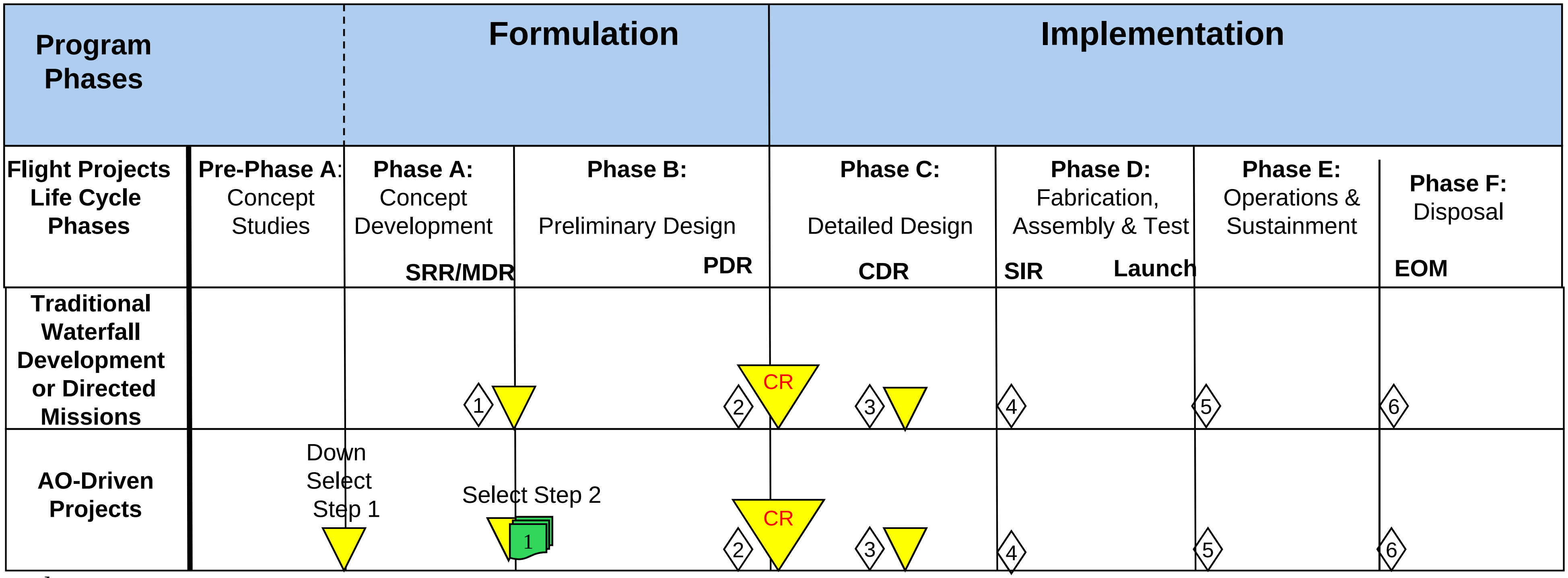
Background

- NASA previously had no current repository of historical project data (programmatic, cost, and technical data)
- In 2004, NASA implemented a procedural requirement in NPR 7120.5 to conduct comprehensive programmatic data collections, called Cost Analysis Data Requirement (CADRe), at key milestones of a projects lifecycle
- Currently over 170 CADRes have been captured and are available for us by NASA analysts to assess trends, identify cost/schedule behaviors, and obtain project specific insight
- As mass is a key parameter for NASA parametric model, a study was commissioned to use CADRe data to determine the historical observed growth for instruments from various points in the lifecycle

CADRe

- CADRe is a three-part document that describes a NASA project at each major milestone (SRR, PDR, CDR, LRD, and End of Mission).
- PART A
  – Narrative project description in Word includes figures and diagrams that note significant changes between milestones.
- PART B
  – Excel templates capture key technical parameters to component-level Work Breakdown Structure (WBS), such as mass, power, and data rates.
- PART C
  – Excel templates capture the project's cost estimate and actual life-cycle costs within NASA cost-estimating WBS to the project's lowest WBS level.

Frequency of CADRes

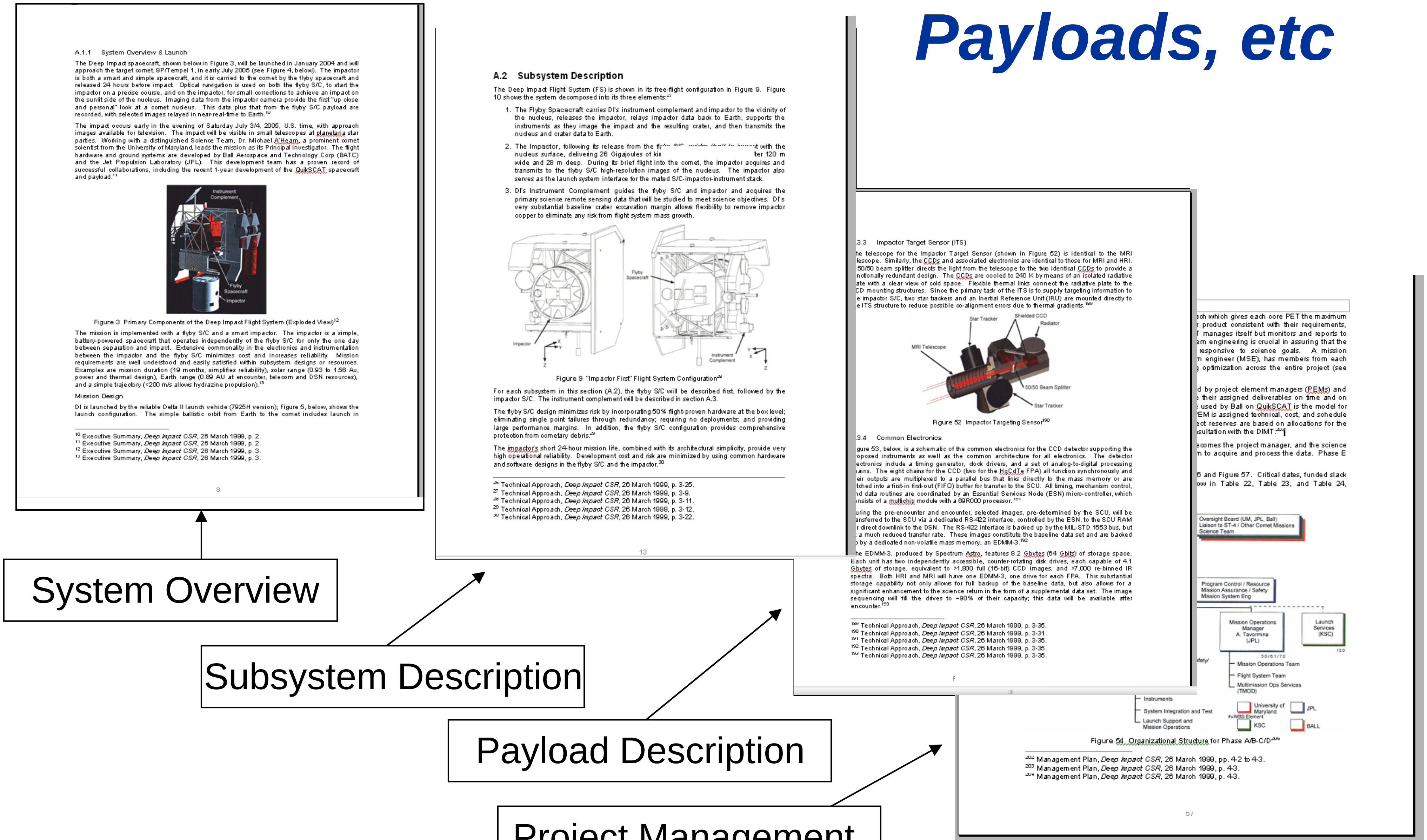


Legend

- Mission Decision Review/ICR
- ① All parts of CADRe due ~30 days after site review
- ① CADRe delivered; based on Concept Study Report (CSR) and winning proposal
- ② All parts of CADRe due ~30 days after PDR site review
- ③ Update as necessary ~30 days after CDR
- ④ Update as necessary ~30 days after SIR (for larger flight projects)
- ⑤ CADRe, All Parts 90 days after launch, as built or as deployed configuration
- ⑥ CADRe, update Part C only at the End of Planned Mission

Part A Example

Provides Descriptive Info of S/C and Payloads, etc



System Overview

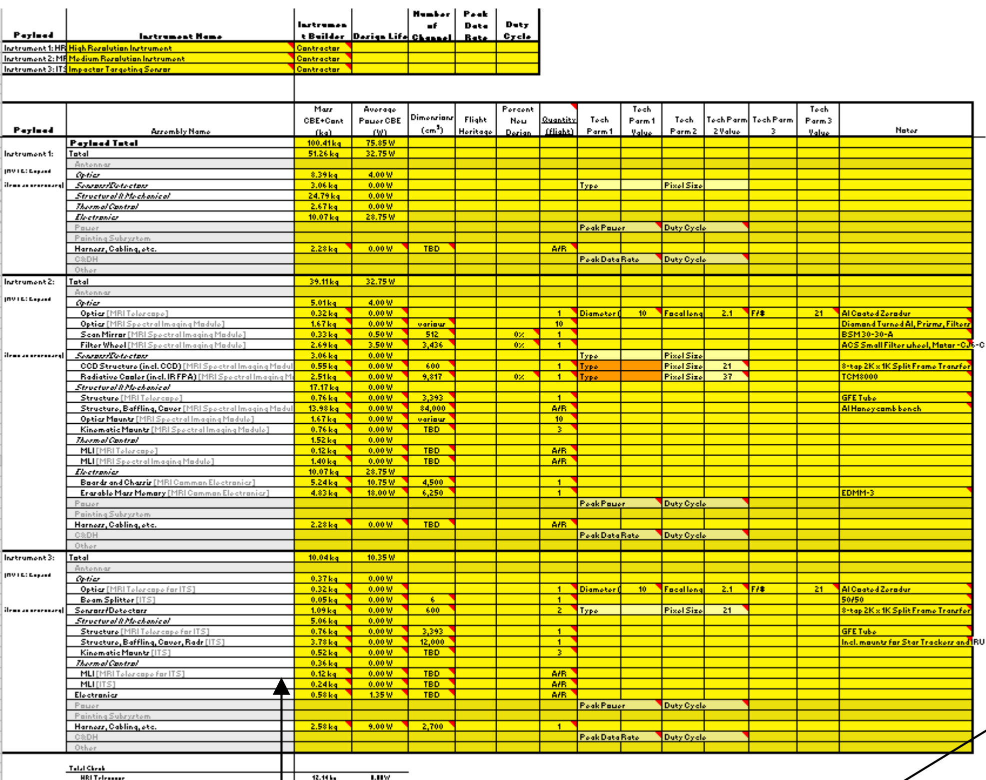
Subsystem Description

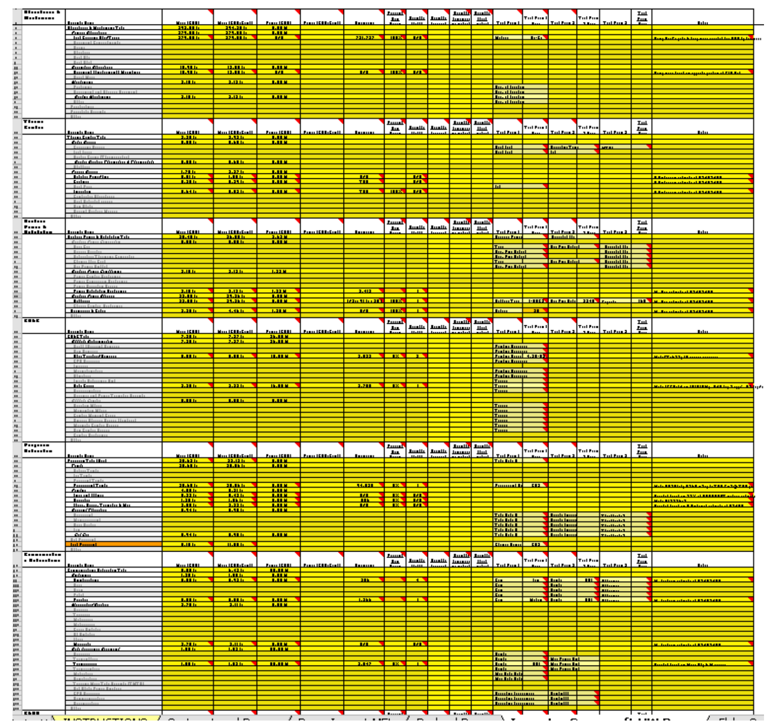
Payload Description

Project Management

Part B Example

Shows the Technical Data (Mass, Power)





System Level Tables

Payload Level Tables

Summary Tables

SYSTEM SUMMARY TABLE

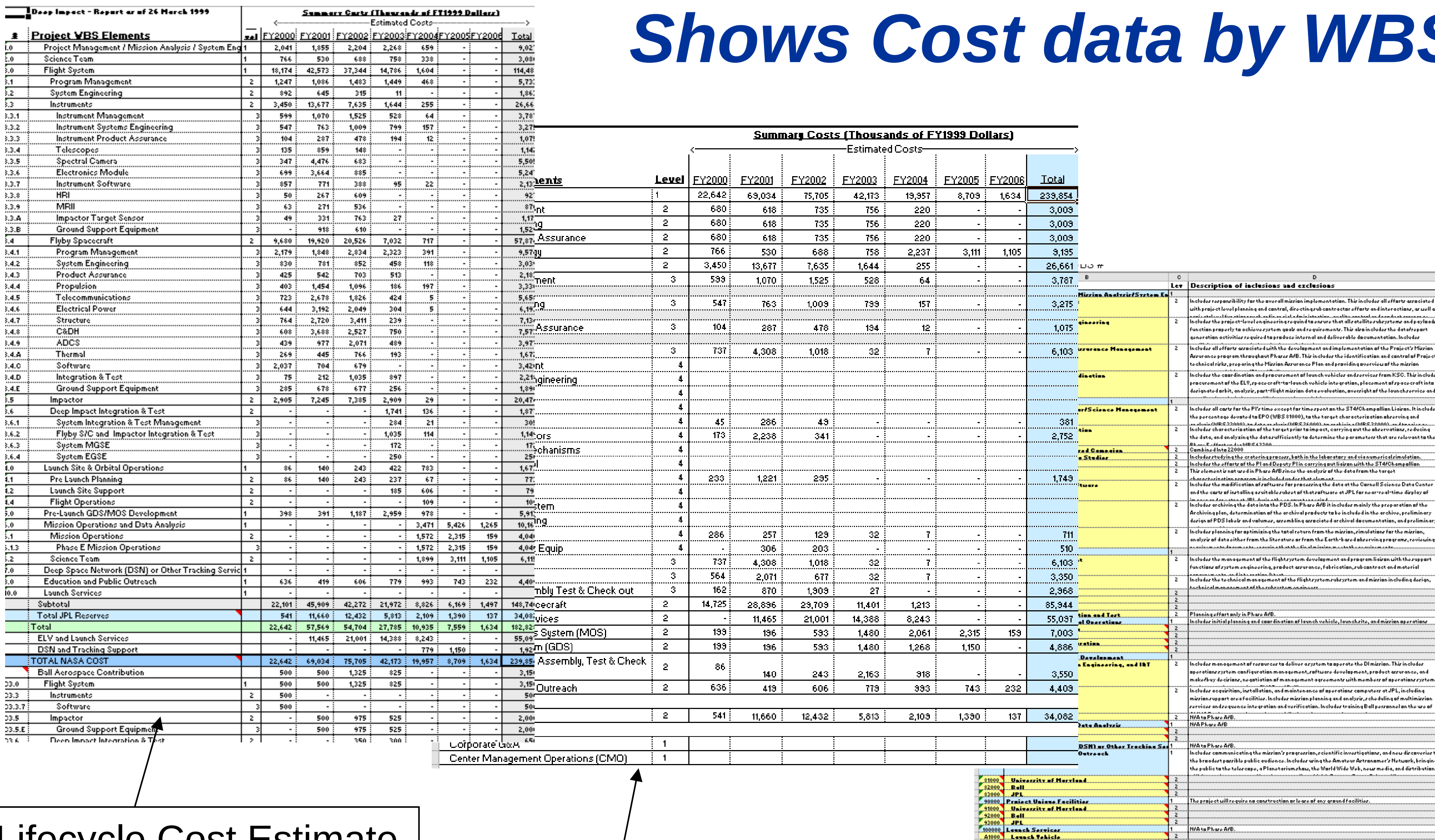
	CBE Mass	CBE Mass w/Contingenc	CBE Power	CBE Power w/Contingenc
Payload Mass	**89.4 kg**	**100.4 kg**	**75.9 W**	
Instrument 1 (HRI)	45.6 kg	51.3 kg	32.8 W	
Instrument 2 (MRI)	34.6 kg	39.1 kg	32.8 W	
Instrument 3 (ITS)	9.1 kg	10.0 kg	10.4 W	
Impactor S/C Dry Mass	**475.8 kg**	**489.4 kg**	**103.6 W**	
Structures & Mechanisms	392.0 kg	394.2 kg	0.0 W	
Thermal	2.3 kg	2.9 kg	0.0 W	
Electrical Power Subsystem	28.5 kg	36.9 kg	2.6 W	
Guidance, Navigation & Control	7.2 kg	7.3 kg	26.0 W	
Propulsion Dry Mass	30.6 kg	32.1 kg	5.0 W	
Telecommunications	5.8 kg	6.4 kg	55.0 W	
Command and Data Handling	9.5 kg	9.6 kg	15.0 W	
Flyby S/C Dry Mass	**323.3 kg**	**359.4 kg**	**278.5 W**	
Structures & Mechanisms	174.4 kg	196.8 kg	5.0 W	
Thermal	8.0 kg	10.5 kg	10.0 W	
Electrical Power Subsystem	50.5 kg	57.8 kg	17.9 W	
Guidance, Navigation & Control	20.1 kg	20.3 kg	40.3 W	
Propulsion Dry Mass	24.5 kg	25.5 kg	70.0 W	
Telecommunications	21.2 kg	22.3 kg	113.4 W	
Command and Data Handling	24.6 kg	26.1 kg	22.0 W	
Propellant & Pressurant	**70.1 kg**	**93.4 kg**		
Impactor Propellant & Pressurant	8.2 kg	11.8 kg		
Flyby S/C Propellant & Pressurant	61.9 kg	81.6 kg		
Total (Dry)	**888.5 kg**	**949.2 kg**	**458.0 W**	
Total (Wet)	**958.6 kg**	**1042.6 kg**		
LV Capability	1144 kg	1144 kg		
Launch Mass Margin	**16.2%**	**8.9%**		

KEY TECHNICAL PARAMETERS

WBS Name	Component	Value
System	Human Rated	No
	Destination	Comet Tempel 1
	Type of Craft	Flyby / Impactor
	Launch Date	1/1/2004
	Average Payload Power (W)	64.8
	GN&C Method	3-axis Stabilization
	Pointing Accuracy	1.7 arcsec
	Pointing Knowledge	1.7 arcsec
	Data Storage	16.4 Gigabytes
	Number of Instruments	3
	Downlink Mode	X-Band
	Downlink Data Rate	128 - 86,600 bps
	Uplink Mode	X-Band
	Uplink Data Rate	8 - 2,000 bps
	Launch Vehicle	Delta II (7925H)
Structures & Mechanisms	Load Carrying Shell/Truss Material	GFRP
Thermal Control	Insulation Type	MLI
Electrical Power & Distribution	Solar Cell Type	GaAs/Ge
	Battery Type	Ni-H2 (SPV)
	Battery Power Output	15 A-hr
Propulsion Subsystem	Monopropellant Thrusters Thrust	2.2 N (16 RCS), 35 N (4)
	Propellant Type	N2H4
Telecommunications Subsyster	Transmit/Receive Band	X-Band
	Flyby/Impactor S/C Crosslink Band	UHF
	Antenna Type	LGA, MGA, HGA
C&DH Subsystem	Solid State Recorder Memory Size	16.4 Gigabytes

Part C Example

Shows Cost data by WBS

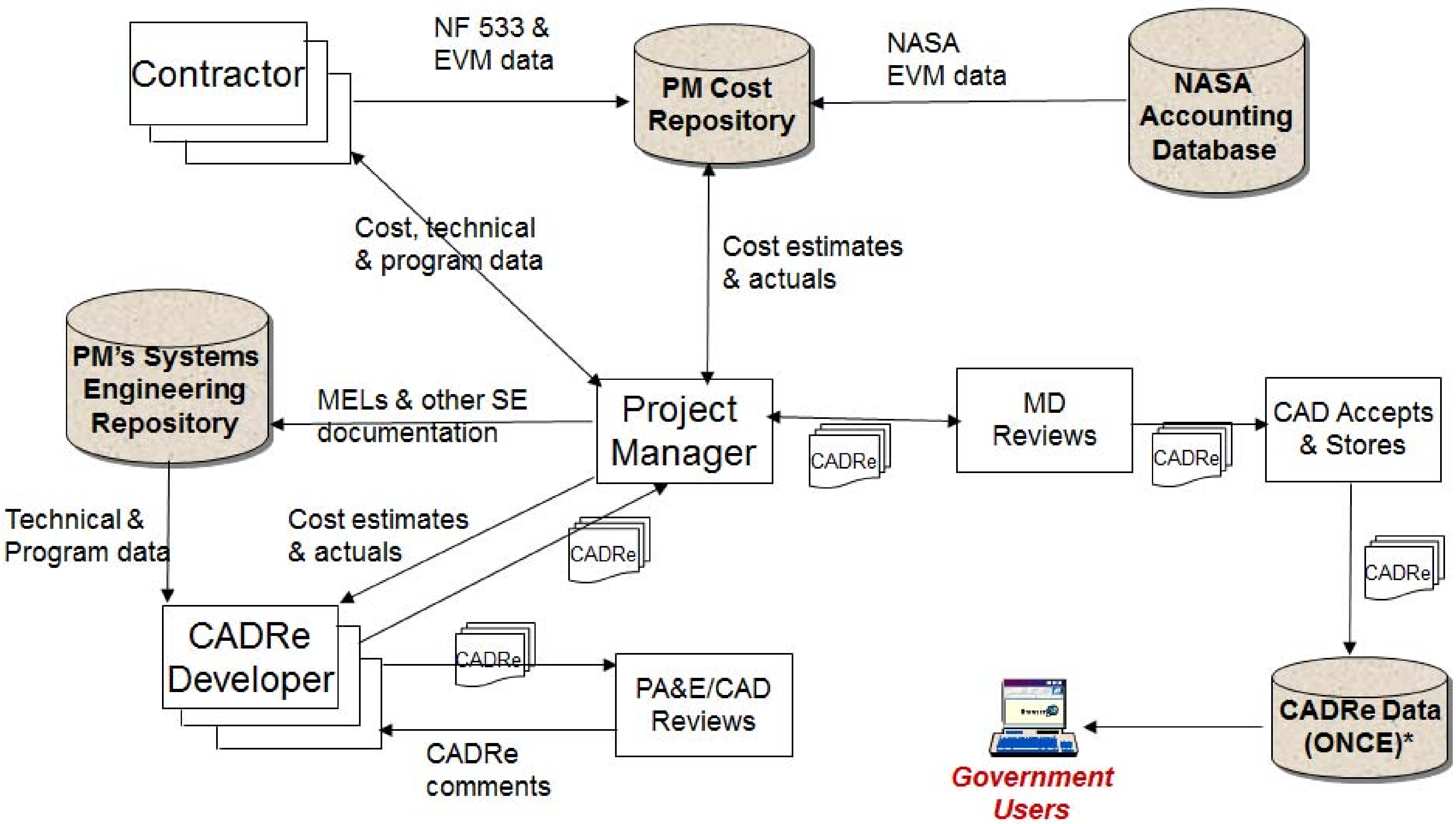


Lifecycle Cost Estimate

Costs Mapped to the NASA WBS

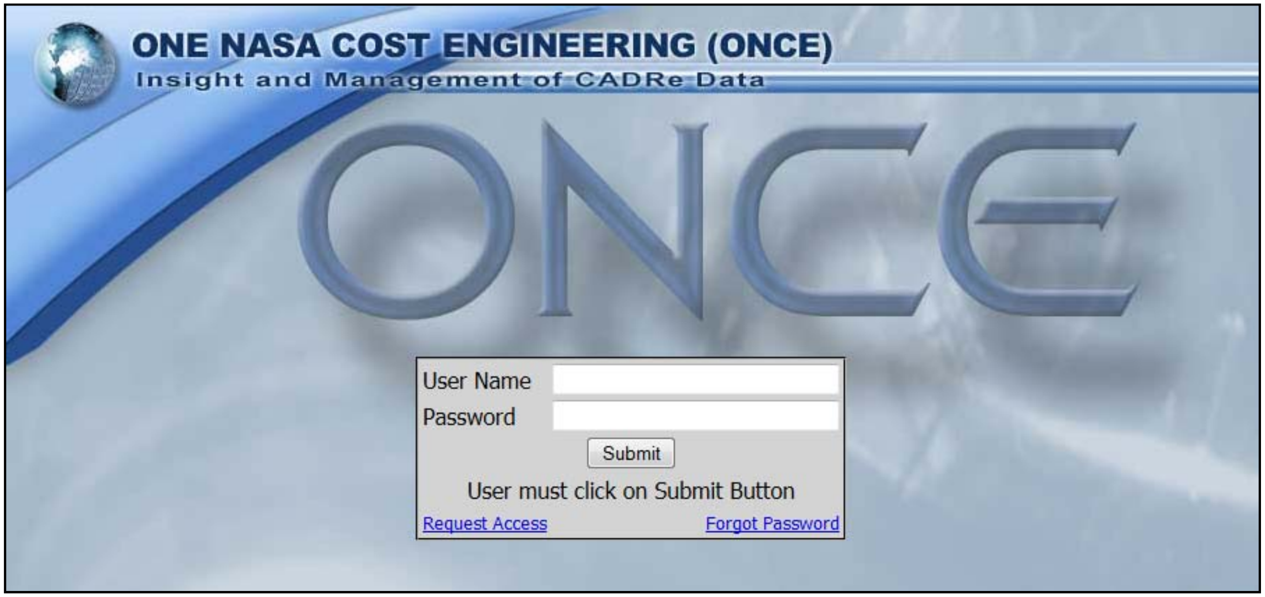
WBS Dictionary

CADRe Process



* One NASA Cost Engineering Database (ONCE)

Completed CADRe's are Stored in ONCE



- NASA-certified Web-based system
- Controlled access
- Automated CADRe search and retrieval

CADRe/ONCE Analysis Product Evolution

Today
110 Instruments
200 CADRes

Initial Mass Growth Study

Enhanced Mass Growth Study
+ 1 additional Metric

Trending on Mass Growth
+2 additional Metrics

Continuous Trending
Additional Metrics
Normalized Dataset

Future
+30 CADRes/Yr
+6 Missions/Yr

Analysis Products

Types of Analysis Products
One Pagers
Datasheets
Published Papers

Bonus
Analysis Trending

Bonus
Consistent Normalized Datasets

Continuous Improvement by Creation and Maintenance of Analysis Products

Study Hypothesis

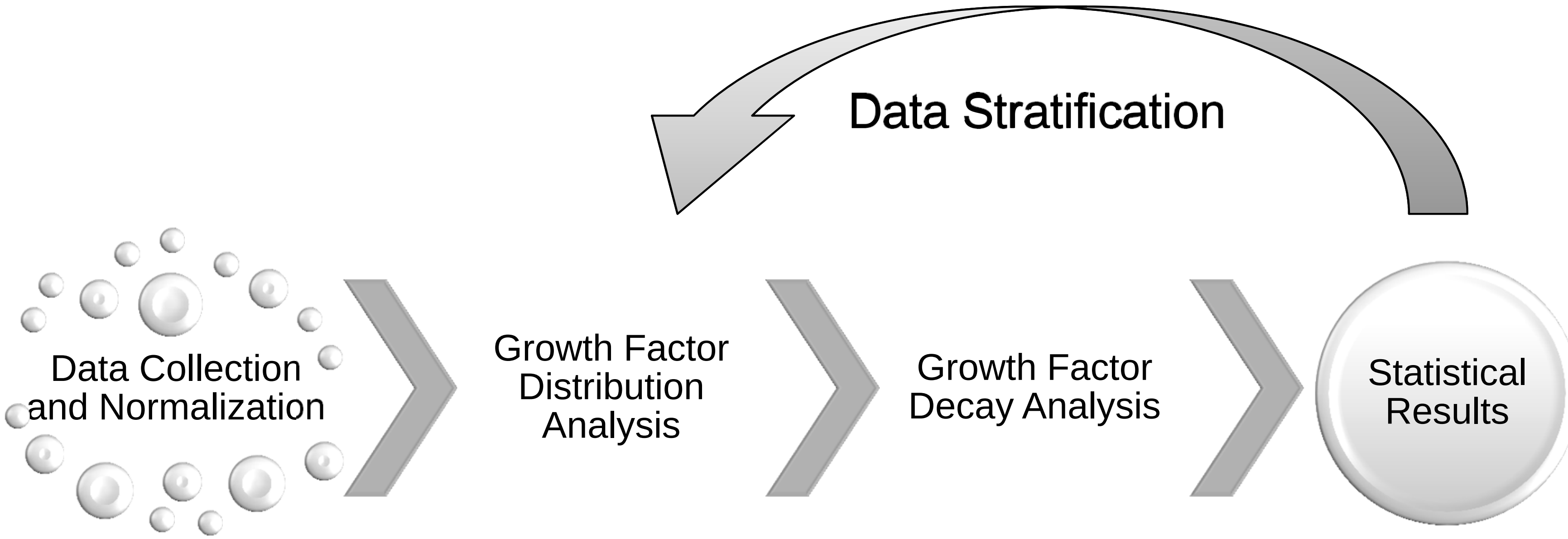
- As the project nears the launch milestone, mass estimates increase in accuracy
  - Mean of the mass values by milestone approaches 1 (zero growth) – Getting better at predicting Launch Mass
  - Standard Deviation decreases as the mass technical baseline matures – Lower variability in mass range
- An Exponential Decay function can be used to model the average decrease in mass growth as the technical baseline

Why Use Mass?

- **Data Availability**
  - Mass is a core technical parameter captured by CADRe
- **Data Usage**
  - Mass is widely used as a variable input parameter for Cost Estimating Relationships (CER) of space instruments
  - Underestimation of mass impacts CER results
- **Risk Input**
  - During development, mass is an estimate
  - "Final" mass may be different than what is estimated
  - Understanding growth potential allows for better quantification of risk inputs

Predicting instrument mass growth is critical and is an integral part of modeling instrument cost and its associated risk

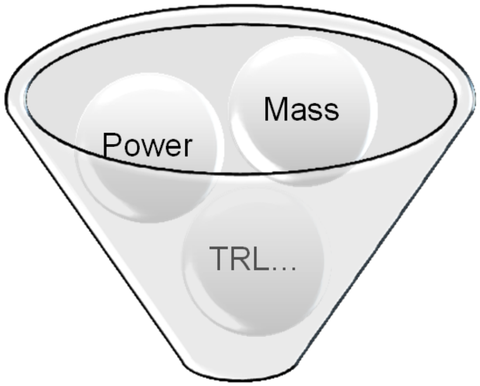
Study Process



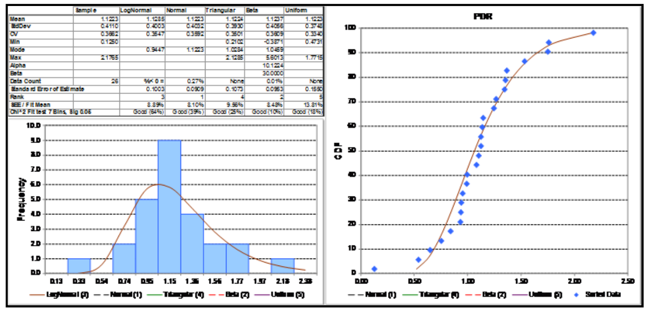
- Assessment and evaluation of source data, extraction, normalization, and format conducted prior to data analysis
- Statistical Analysis software facilitates Growth Factor and Decay analysis – used COTS tools (Excel and CO$TAT from ACEIT Software suite)
- Data Stratifications include selection of Milestone groups or technical characteristics of dataset instruments

Analysis Framework

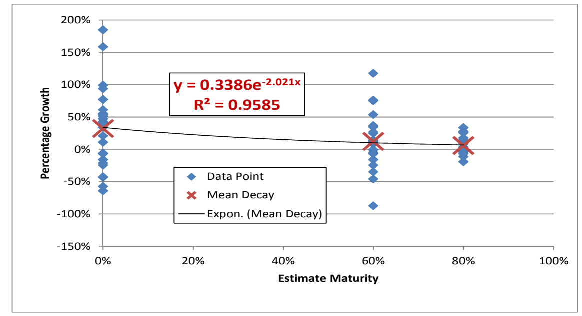
Data Collection

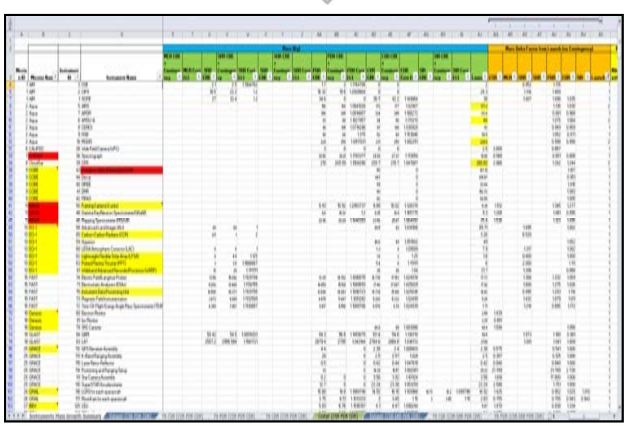


Growth Factor Analysis



Decay Analysis





Consolidated Datasheet

	B	C	D	E
3	Observations	CSR	PDR	CDR
4	Variable ID	CSR	PDR	CDR
5	36	0.568	0.65052356	0.808458723
6	50	1.512	1.34519573	1.277027027
7	48	1.207792208	1.081395349	0.9994652406
8	46	1.535714286	1.122715405	1.095076401
9	112	0.574879227	0.540909091	1
10	113	0.357142857	0.125	1
11	115	0.84	0.84	1
12	110	2.586046512	1.751181102	1
13	116	1.425023878	0.951530612	1.025429553
14	117	0.754666667	0.754666667	0.943333333
15	125	1.470430108	0.938250429	1.334146341
16	123	1.373239437	1.125541126	0.97135741
17	124	1.552429668	1.144203582	1.08489723
18	153	1.768867925	1.76056338	1.143292683
19	156	2.846153846	2.176470588	1.088235294
20	149	0.424567189	1.366047745	0.973534972
21	154	1.990825688	1.247126437	1.269005848
22	155	1.535714286	1.535714286	1.172727273
23	173	1.33977591	1.104491398	1.033960959
24	211	1.936810631	1.355767442	1.256964209
25	359	1.407983193	1.138189291	1.025633178
26	389	0.786966487	0.9925	1.017948718
27	394	1.61106656	1.265511811	0.88677996
28	390	0.939968312	0.939968312	1.00410594
29	391	0.9308444	0.9308444	0.930005507

Formatted Analysis Worksheets

Calculation Techniques

- **Milestone Growth Factors**
  - Growth factors for mass developed for each mission from each milestone to final launch value
  - Two techniques used
    - Technique 1: CDF development and mean value determination from Excel
    - Technique 2: Distribution and statistics determined from CO$TAT best-fit analysis

- **Decay Equation**
  - Identify a group of instruments with data across all targeted milestones
  - Determine mean growth factors for each milestone
  - Conduct regression analysis
    - Excel using graphing capability
      - Plot chart of Mean Percentage Growth
      - Run exponential regression through points and display equation
    - Excel using a formula
      - INDEX(LINEST(LN(MEAN PERCENTAGE GROWTH VALUES),ESTIMATE MATURITY),1)
    - CO$TAT using Non-linear analysis feature
      - Estimate Maturity = a * EXP(b* Mean Percentage Growth)
      - Calculate decay constant = b

Decay Analysis Results Can be Used to Create a Continuous Mass Growth Model

Basic Model

Instrument Mass Growth

$$\boldsymbol{M_{Adj}} \equiv M\left(e^{-bt}\left(\boldsymbol{K_{GF}}-1\right)+1\right)$$

$\boldsymbol{M_{Adj}}$ = Growth-adjusted Mass Estimate Distribution

$\boldsymbol{K_{GF}}$ = Baseline (@ CSR) Mass Estimate Growth Factor Distribution

M = Technical Baseline Point Estimate of Mass

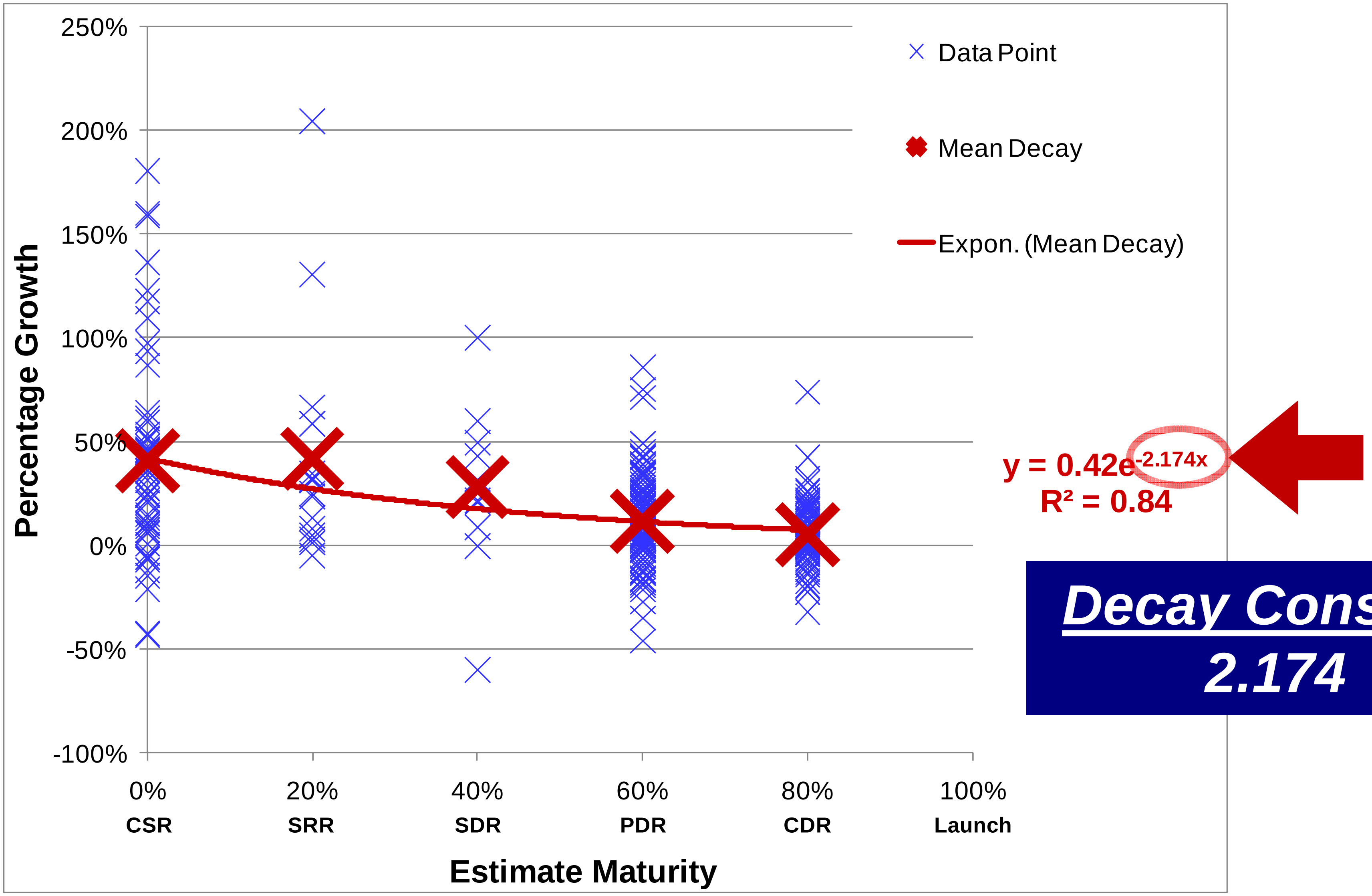
b = Mass Growth Decay Constant

t = Estimate Maturity Parameter

(CSR/SRR = 20%; SDR=40%; PDR=60%; CDR=80%; Launch=100%)

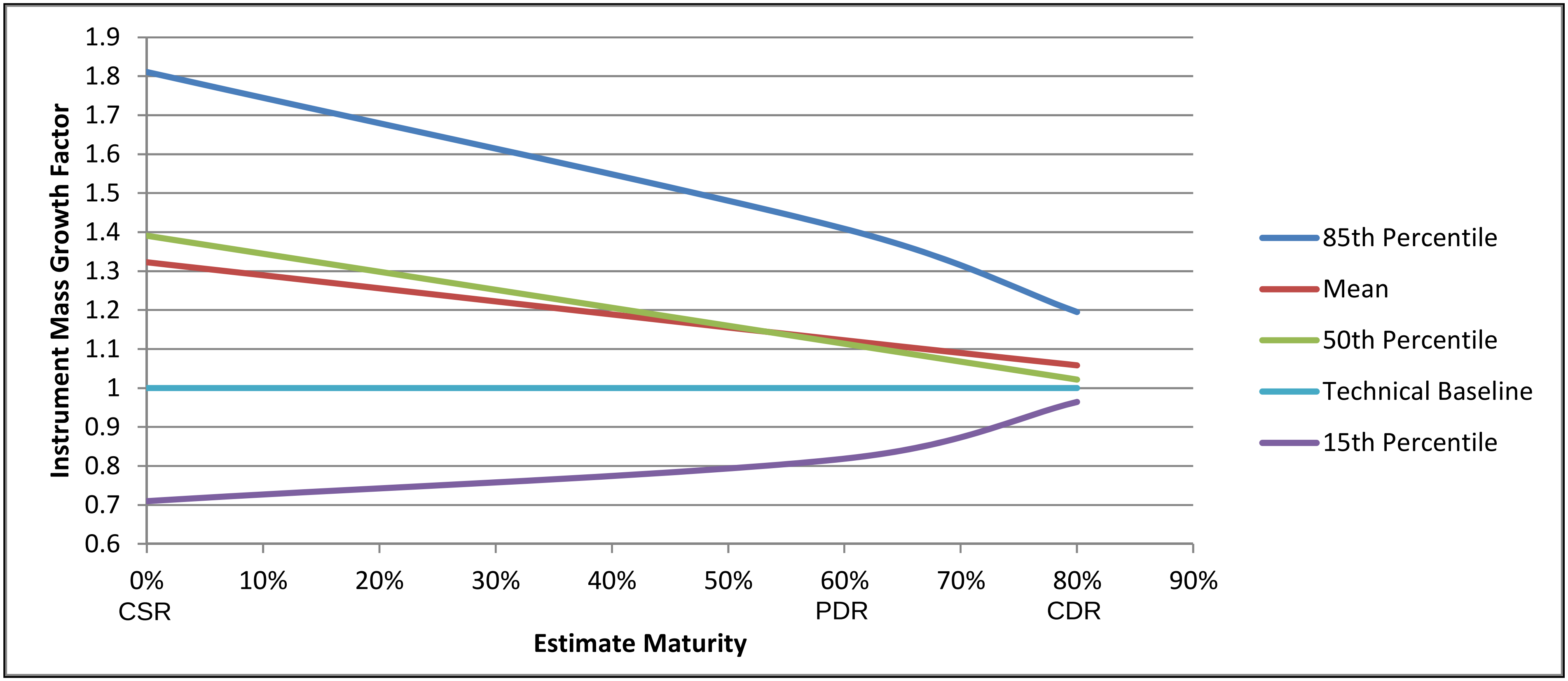
Enables Analysts to Use at any Point in Design Cycle and not just at Milestones

Deriving a Decay Constant from Mass Growth Data



Decay Constant
2.174

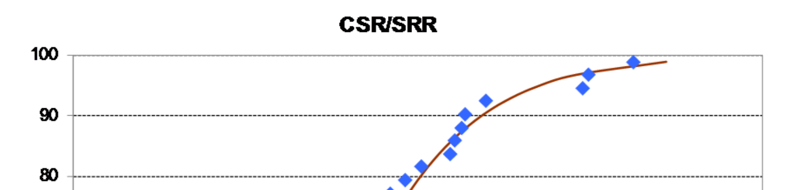
Example of Continuous Mass Growth Decay Model



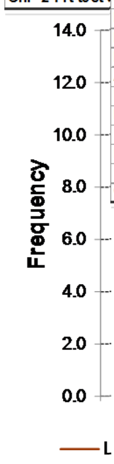
Enhances Analyst Capability to Specify Mass Uncertainty Ranges for CERs and SERs

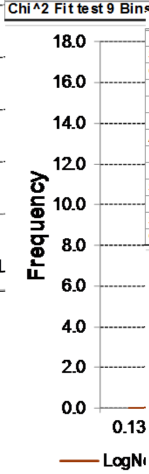
Mass Growth Distributions
Common Milestones – CADRe Data

	Sample	LogNormal	Normal	Triangular	Beta	Uniform
Mean	1.3787	1.3853	1.3787	1.3788	1.3800	1.3787
StdDev	0.5359	0.5269	0.5272	0.5210	0.5309	0.5023
CV	0.3887	0.3804	0.3824	0.3779	0.3847	0.3643
Min	0.3571			0.2284	-0.0626	0.5087
Mode	1.5357	1.1312	1.3787	1.1564	1.2101	
Max	2.8462			2.7515	8.5258	2.2486
Alpha					5.9756	
Beta					29.6004	
Data Count	46	% < 0 =	0.45%	None	0.00%	None
Standard Erro						
Rank						
SEE / Fit Mear						
Chi^2 Fit test						

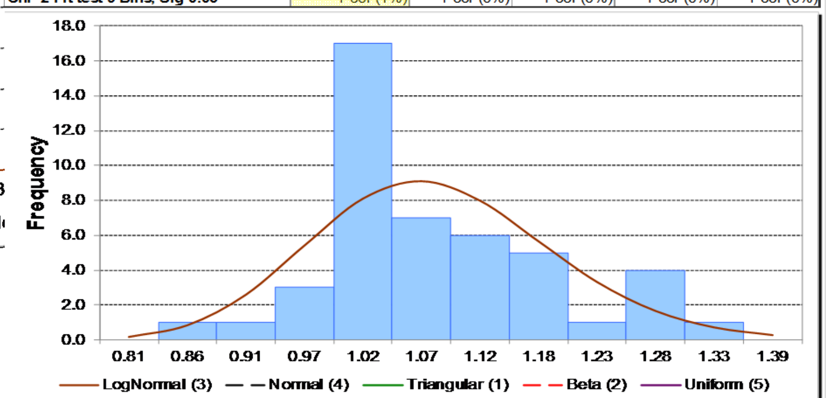


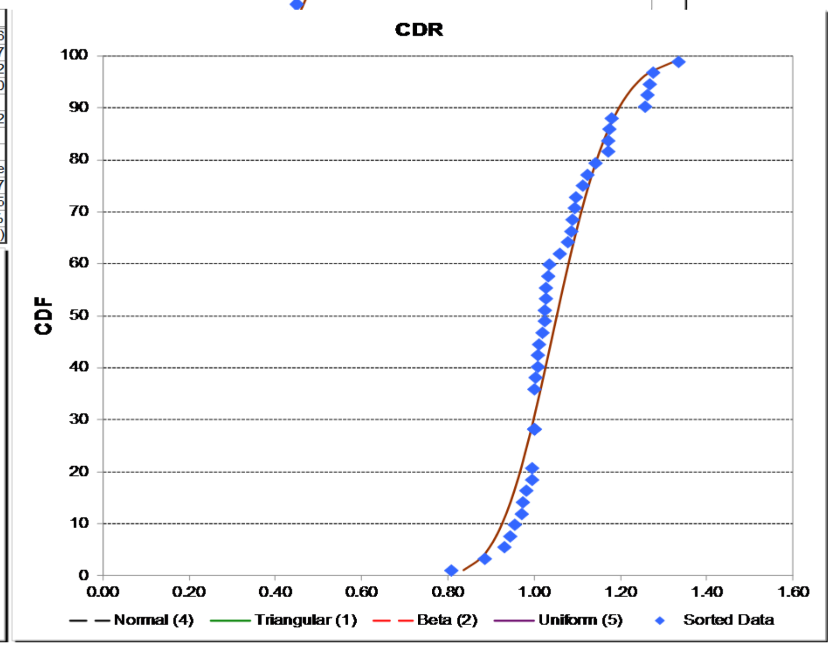
	Sample	LogNormal	Normal	Triangular	Beta	Uniform
Mean	1.1426	1.1447	1.1426	1.1426	1.1430	1.1426
StdDev	0.3350	0.3225	0.3226	0.3144	0.3219	0.2969
CV	0.2932	0.2817	0.2823	0.2751	0.2816	0.2598
Min	0.1250			0.4140	-0.1470	0.6284
Mode		1.0208	1.1426	1.0655	1.0896	
Max	2.1765			1.9483	4.5181	1.6568
Alpha					11.3457	
Beta					29.6835	
Data Count	46	% < 0 =	0.02%	None	0.00%	None
Standard Error of Estimate		0.0937	0.0946	0.1112	0.0973	0.1506
Rank		1	2	4	3	5
SEE / Fit Mean		8.19%	8.28%	9.74%	8.52%	13.18%
Chi^2 Fit test 9 Bins, Sig 0.05		Good (10%)	Good (19%)	Poor (2%)	Poor (1%)	Poor (2%)



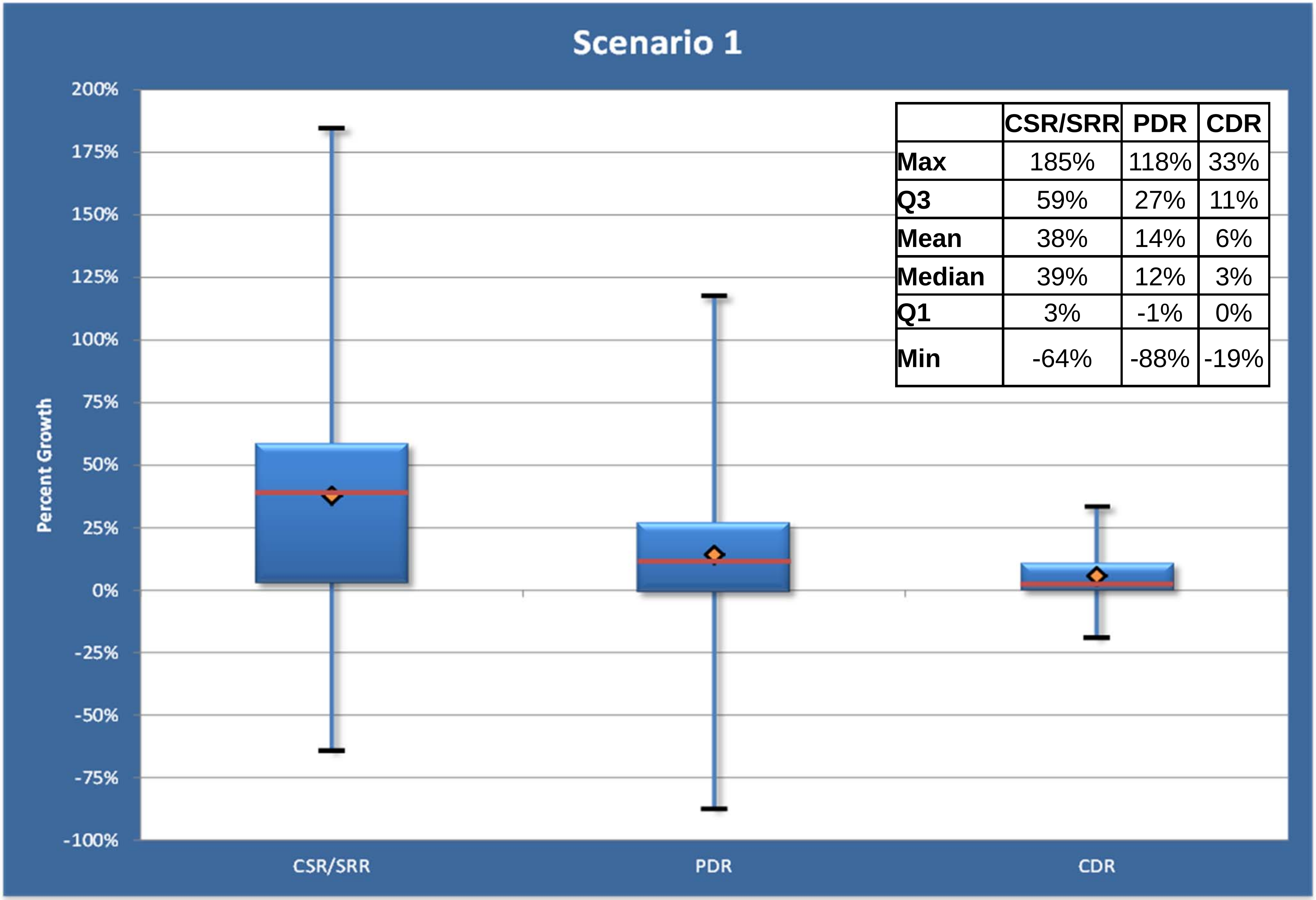


	Sample	LogNormal	Normal	Triangular	Beta	Uniform
Mean	1.0576	1.0576	1.0575	1.0576	1.0578	1.0576
StdDev	0.1080	0.1062	0.1044	0.1043	0.1048	0.0997
CV	0.1021	0.1004	0.0987	0.0986	0.0991	0.0942
Min	0.8085			0.8526	0.9046	0.8850
Mode	1.0000	1.0418	1.0575	0.9764	0.9667	
Max	1.3341			1.3439	1.5016	1.2302
Alpha					1.3320	
Beta					3.8590	
Data Count	46	% < 0 =	0.00%	None	None	None
Standard Error of Estimate		0.0258	0.0294	0.0253	0.0256	0.0397
Rank		3	4	1	2	5
SEE / Fit Mean		2.44%	2.78%	2.39%	2.42%	3.75%
Chi^2 Fit test 9 Bins, Sig 0.05		Poor (1%)	Poor (0%)	Poor (0%)	Poor (0%)	Poor (0%)





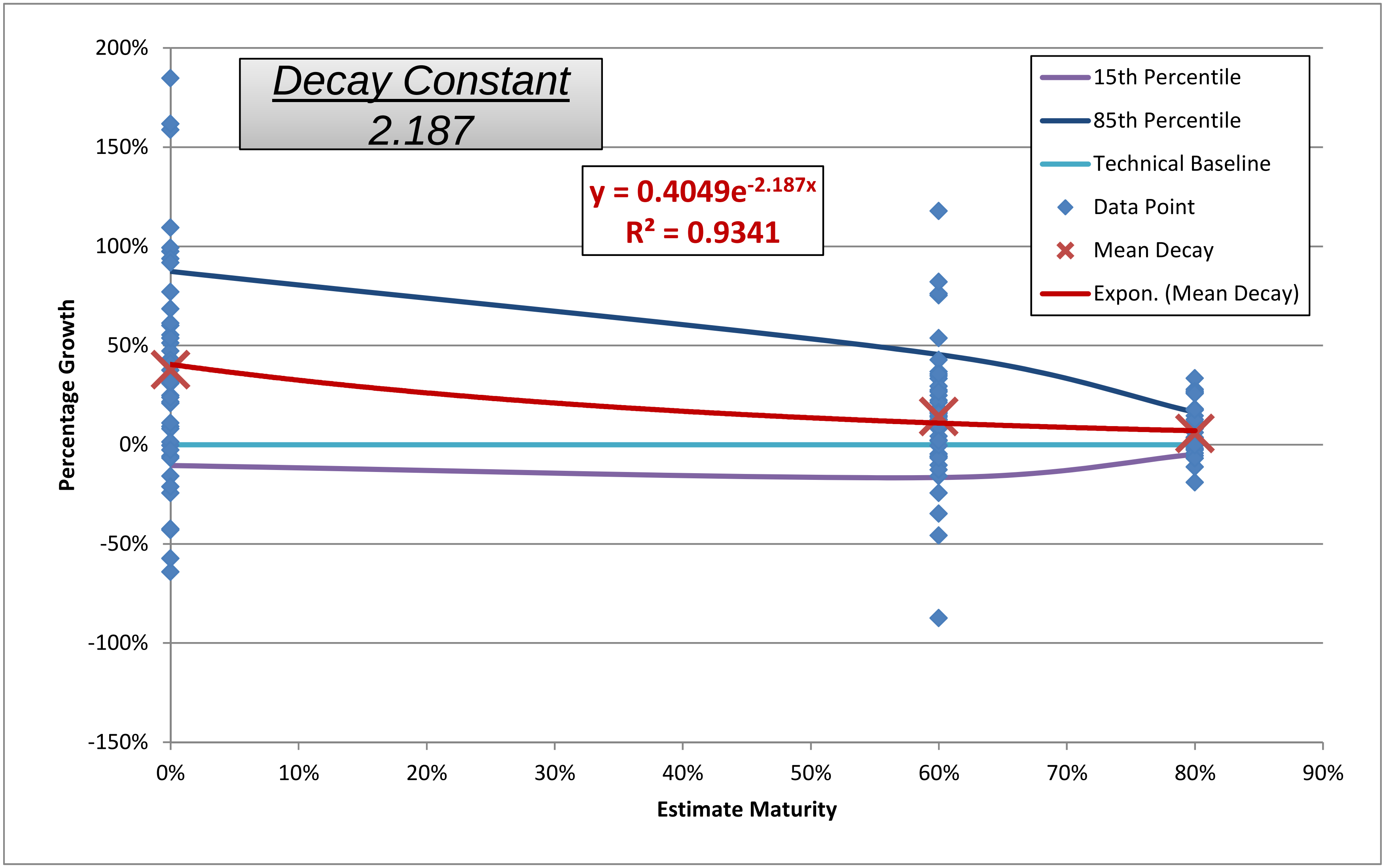
Percent Growth by Milestone
Common Milestones – CADRe Data



	CSR/SRR	PDR	CDR
Max	185%	118%	33%
Q3	59%	27%	11%
Mean	38%	14%	6%
Median	39%	12%	3%
Q1	3%	-1%	0%
Min	-64%	-88%	-19%

Mass Growth Decay Model

Common Milestones – CADRe Data



CSR/SRR = 0%; SDR = 40%; PDR = 60%; CDR = 80%; Launch = 100%

Next Steps

- Finalize Study Results
  - General results for all NASA instruments and Spacecraft
  - Segmentation analysis (e.g., instrument type, destination)
- Publish one-pager fact sheets to help NASA analysts in the field