Probabilistic Mass Growth Uncertainties

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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.

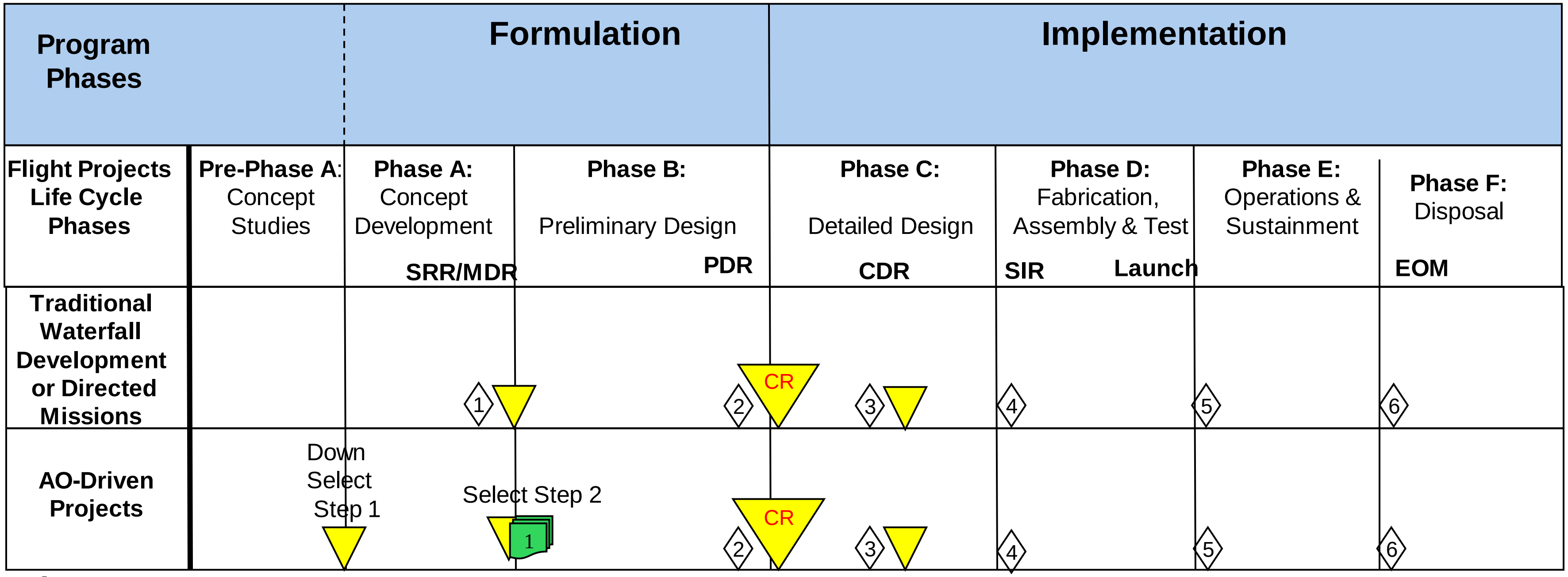
Background

- 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

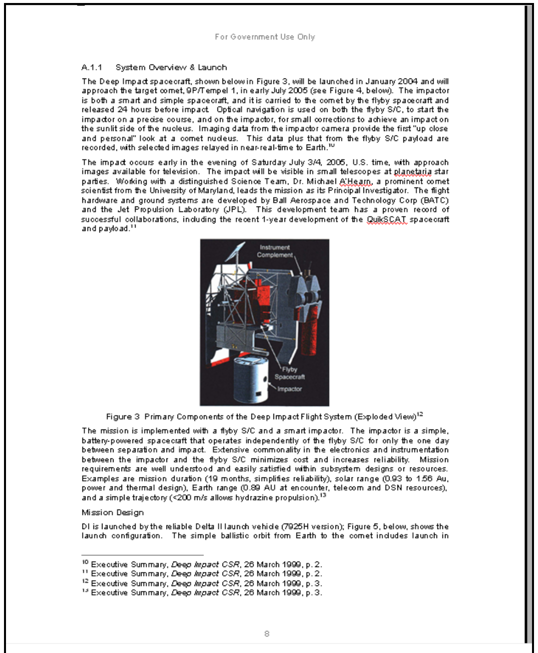
(4) Update as necessary ~30 days after SIR (for larger flight projects)

(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



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A.1.1 System Overview & Launch

The Deep Impact spacecraft, shown below in Figure 3, will be launched in January 2004 and will approach the target comet, 9P/Tempel 1, in early July 2005 (see Figure 4, below). The impactor is both a smart and simple spacecraft, and it is carried to the comet by the flyby spacecraft and released 24 hours before impact. Optical navigation is used on both the flyby S/C, to start the impactor on a precise course, and on the impactor, for small corrections to achieve an impact on the sunlit side of the nucleus. Imaging data from the impactor camera provide the first "up close and personal" look at a comet nucleus. This data plus that from the flyby S/C payload are recorded, with selected images relayed in near-real-time to Earth.[10]

The impact occurs early in the evening of Saturday July 3/4, 2005, U.S. time, with approach images available for television. The impact will be visible in small telescopes at planetaria star parties. Working with a distinguished Science Team, Dr. Michael A'Hearn, a prominent comet scientist from the University of Maryland, leads the mission as its Principal Investigator. The flight hardware and ground systems are developed by Ball Aerospace and Technology Corp (BATC) and the Jet Propulsion Laboratory (JPL). This development team has a proven record of successful collaborations, including the recent 1-year development of the QuikSCAT spacecraft and payload.[11]

Figure 3 Primary Components of the Deep Impact Flight System (Exploded View)[12]

The mission is implemented with a flyby S/C and a smart impactor. The impactor is a simple, battery-powered spacecraft that operates independently of the flyby S/C for only the one day between separation and impact. Extensive commonality in the electronics and instrumentation between the impactor and the flyby S/C minimizes cost and increases reliability. Mission requirements are well understood and easily satisfied within subsystem designs or resources. Examples are mission duration (19 months, simplifies reliability), solar range (0.93 to 1.56 Au, power and thermal design), Earth range (0.89 AU at encounter, telecom and DSN resources), and a simple trajectory (<200 m/s allows hydrazine propulsion).[13]

Mission Design

DI is launched by the reliable Delta II launch vehicle (7925H version); Figure 5, below, shows the launch configuration. The simple ballistic orbit from Earth to the comet includes launch in

[10] Executive Summary, *Deep Impact CSR*, 26 March 1999, p. 2.
[11] Executive Summary, *Deep Impact CSR*, 26 March 1999, p. 2.
[12] Executive Summary, *Deep Impact CSR*, 26 March 1999, p. 3.
[13] Executive Summary, *Deep Impact CSR*, 26 March 1999, p. 3.

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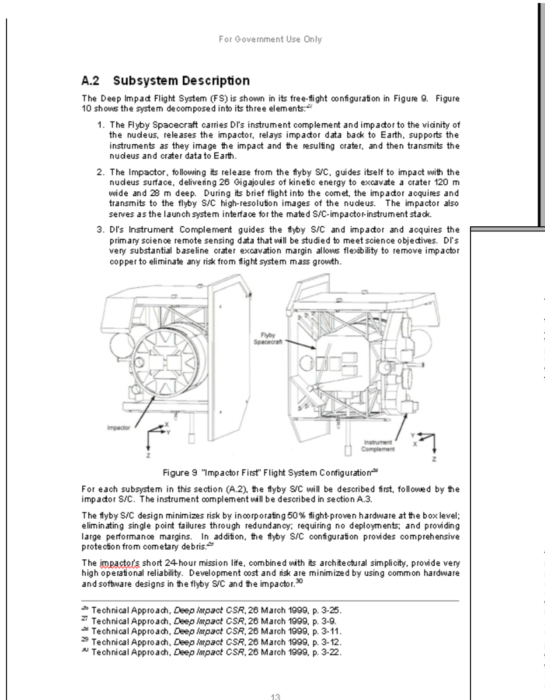

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A.2 Subsystem Description

The Deep Impact Flight System (FS) is shown in its free-flight configuration in Figure 9. Figure 10 shows the system decomposed into its three elements:[27]

1. The Flyby Spacecraft carries DI's instrument complement and impactor to the vicinity of the nucleus, releases the impactor, relays impactor data back to Earth, supports the instruments as they image the impact and the resulting crater, and then transmits the nucleus and crater data to Earth.
2. The Impactor, following its release from the flyby S/C, guides itself to impact with the nucleus surface, delivering 26 Gigajoules of kinetic energy to excavate a crater 120 m wide and 28 m deep. During its brief flight into the comet, the impactor acquires and transmits to the flyby S/C high-resolution images of the nucleus. The impactor also serves as the launch system interface for the mated S/C-impactor-instrument stack.
3. DI's Instrument Complement guides the flyby S/C and impactor and acquires the primary science remote sensing data that will be studied to meet science objectives. DI's very substantial baseline crater excavation margin allows flexibility to remove impactor copper to eliminate any risk from flight system mass growth.

Figure 9 "Impactor First" Flight System Configuration[28]

For each subsystem in this section (A.2), the flyby S/C will be described first, followed by the impactor S/C. The instrument complement will be described in section A.3.

The flyby S/C design minimizes risk by incorporating 50% flight-proven hardware at the box level; eliminating single point failures through redundancy; requiring no deployments; and providing large performance margins. In addition, the flyby S/C configuration provides comprehensive protection from cometary debris.[29]

The impactor's short 24-hour mission life, combined with its architectural simplicity, provide very high operational reliability. Development cost and risk are minimized by using common hardware and software designs in the flyby S/C and the impactor.[30]

[26] Technical Approach, *Deep Impact CSR*, 26 March 1999, p. 3-25.
[27] Technical Approach, *Deep Impact CSR*, 26 March 1999, p. 3-9.
[28] Technical Approach, *Deep Impact CSR*, 26 March 1999, p. 3-11.
[29] Technical Approach, *Deep Impact CSR*, 26 March 1999, p. 3-12.
[30] Technical Approach, *Deep Impact CSR*, 26 March 1999, p. 3-22.

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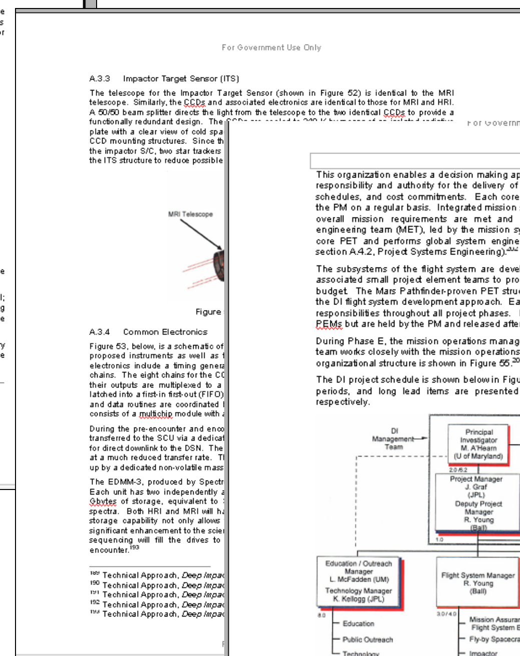

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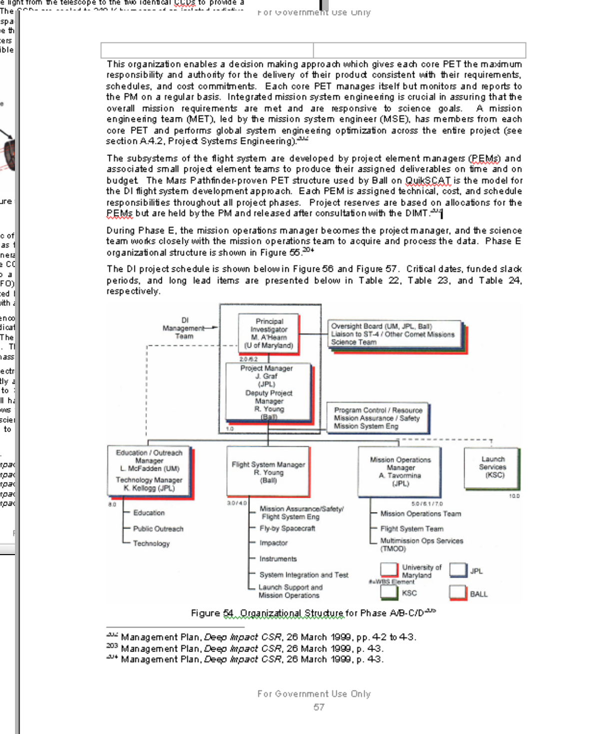
A.3.3 Impactor Target Sensor (ITS)

The telescope for the Impactor Target Sensor (shown in Figure 52) is identical to the MRI telescope. Similarly, the CCDs and associated electronics are identical to those for MRI and HRI.

A.3.4 Common Electronics



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This organization enables a decision making approach which gives each core PET the maximum responsibility and authority for the delivery of their product consistent with their requirements, schedules, and cost commitments. Each core PET manages itself but monitors and reports to the PM on a regular basis. Integrated mission system engineering is crucial in assuring that the overall mission requirements are met and are responsive to science goals. A mission engineering team (MET), led by the mission system engineer (MSE), has members from each core PET and performs global system engineering optimization across the entire project (see section A.4.2, Project Systems Engineering).[202]

The subsystems of the flight system are developed by project element managers (PEMs) and associated small project element teams to produce their assigned deliverables on time and on budget. The Mars Pathfinder-proven PET structure used by Ball on QuikSCAT is the model for the DI flight system development approach. Each PEM is assigned technical, cost, and schedule responsibilities throughout all project phases. Project reserves are based on allocations for the PEMs but are held by the PM and released after consultation with the DIMT.[203]

During Phase E, the mission operations manager becomes the project manager, and the science team works closely with the mission operations team to acquire and process the data. Phase E organizational structure is shown in Figure 55.[204]

The DI project schedule is shown below in Figure 56 and Figure 57. Critical dates, funded slack periods, and long lead items are presented below in Table 22, Table 23, and Table 24, respectively.

Figure 54 Organizational Structure for Phase A/B-C/D[205]

[202] Management Plan, *Deep Impact CSR*, 26 March 1999, pp. 4-2 to 4-3.
[203] Management Plan, *Deep Impact CSR*, 26 March 1999, p. 4-3.
[204] Management Plan, *Deep Impact CSR*, 26 March 1999, p. 4-3.

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System Overview

Subsystem Description

Payload Description

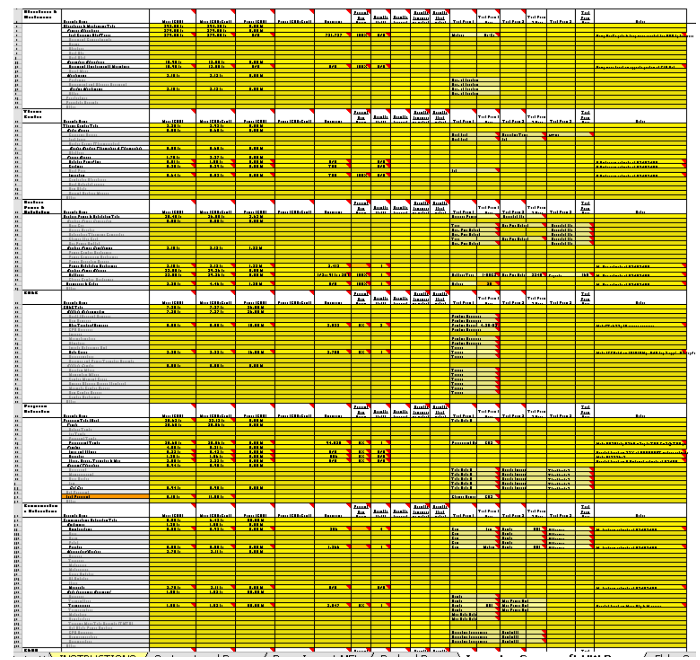
Project Management

Part B Example

Shows the Technical Data (Mass, Power)

Payload	Instrument Name	Instrument Builder	Design Life	Number of Channel	Peak Data Rate	Duty Cycle
Instrument 1: HR	High Resolution Instrument	Contractor				
Instrument 2: MR	Medium Resolution Instrument	Contractor				
Instrument 3: ITS	Impactor Targeting Sensor	Contractor				

Payload	Assembly Name	Mass CBE+Cont (kg)	Average Power CBE (W)	Dimensions (cm³)	Flight Heritage	Percent New Design	Quantity (flight)	Tech Parm 1	Tech Parm 1 Value	Tech Parm 2	Tech Parm 2 Value	Tech Parm 3	Tech Parm 3 Value	Notes
	Payload Total	100.41 kg	75.85 W											
Instrument 1:	Total	51.26 kg	32.75 W											
	Antennas													
[NOTE: Expand	*Optics*	8.39 kg	4.00 W											
items as necessary]	*Sensors/Detectors*	3.06 kg	0.00 W					Type		Pixel Size				
	Structural & Mechanical	24.79 kg	0.00 W											
	Thermal Control	2.67 kg	0.00 W											
	Electronics	10.07 kg	28.75 W											
	Power							Peak Power		Duty Cycle				
	Pointing Subsystem													
	Harness, Cabling, etc.	2.28 kg	0.00 W	TBD			A/R							
	C&DH							Peak Data Rate		Duty Cycle				
	Other													
Instrument 2:	Total	39.11 kg	32.75 W											
	Antennas													
[NOTE: Expand	*Optics*	5.01 kg	4.00 W											
	Optics [MRI Telescope]	0.32 kg	0.00 W				1	Diameter (	10	Focal leng	2.1	F/#	21	Al Coated Zerodur
	Optics [MRI Spectral Imaging Module]	1.67 kg	0.00 W	various			10							Diamond Turned Al, Prisms, Filters
	Scan Mirror [MRI Spectral Imaging Module]	0.33 kg	0.50 W	512		0%	1							BSM30-30-A
	Filter Wheel [MRI Spectral Imaging Module]	2.69 kg	3.50 W	3,436		0%	1							ACS Small Filter wheel, Motor -CJ6-C
items as necessary]	*Sensors/Detectors*	3.06 kg	0.00 W					Type		Pixel Size				
	CCD Structure (incl. CCD) [MRI Spectral Imaging Modul	0.55 kg	0.00 W	600			1	Type		Pixel Size	21			8-tap 2K x 1K Split Frame Transfer
	Radiative Cooler (incl. IR FPA) [MRI Spectral Imaging M	2.51 kg	0.00 W	9,817		0%	1	Type		Pixel Size	37			TCM8000
	Structural & Mechanical	17.17 kg	0.00 W											
	Structure [MRI Telescope]	0.76 kg	0.00 W	3,393			1							GFE Tube
	Structure, Baffling, Cover [MRI Spectral Imaging Modul	13.98 kg	0.00 W	84,000			A/R							Al Honeycomb bench
	Optics Mounts [MRI Spectral Imaging Module]	1.67 kg	0.00 W	various			10							
	Kinematic Mounts [MRI Spectral Imaging Module]	0.76 kg	0.00 W	TBD			3							
	Thermal Control	1.52 kg	0.00 W											
	MLI [MRI Telescope]	0.12 kg	0.00 W	TBD			A/R							
	MLI [MRI Spectral Imaging Module]	1.40 kg	0.00 W	TBD			A/R							
	Electronics	10.07 kg	28.75 W											
	Boards and Chassis [MRI Common Electronics]	5.24 kg	10.75 W	4,500			1							
	Erasable Mass Memory [MRI Common Electronics]	4.83 kg	18.00 W	6,250			1							EDMM-3
	Power							Peak Power		Duty Cycle				
	Pointing Subsystem													
	Harness, Cabling, etc.	2.28 kg	0.00 W	TBD			A/R							
	C&DH							Peak Data Rate		Duty Cycle				
	Other													
Instrument 3:	Total	10.04 kg	10.35 W											
	Antennas													
[NOTE: Expand	*Optics*	0.37 kg	0.00 W											
	Optics [MRI Telescope for ITS]	0.32 kg	0.00 W				1	Diameter (	10	Focal leng	2.1	F/#	21	Al Coated Zerodur
	Beam Splitter [ITS]	0.05 kg	0.00 W	6			1							50/50
items as necessary]	Sensors/Detectors	1.09 kg	0.00 W	600			2	Type		Pixel Size	21			8-tap 2K x 1K Split Frame Transfer
	Structural & Mechanical	5.06 kg	0.00 W											
	Structure [MRI Telescope for ITS]	0.76 kg	0.00 W	3,393			1							GFE Tube
	Structure, Baffling, Cover, Rads [ITS]	3.78 kg	0.00 W	12,000			1							Incl. mounts for Star Trackers and IRU
	Kinematic Mounts [ITS]	0.52 kg	0.00 W	TBD			3							
	Thermal Control	0.36 kg	0.00 W											
	MLI [MRI Telescope for ITS]	0.12 kg	0.00 W	TBD			A/R							
	MLI [ITS]	0.24 kg	0.00 W	TBD			A/R							
	Electronics	0.58 kg	1.35 W	TBD			A/R							
	Power							Peak Power		Duty Cycle				
	Pointing Subsystem													
	Harness, Cabling, etc.	2.58 kg	9.00 W	2,700			1							
	C&DH							Peak Data Rate		Duty Cycle				
	Other													
	Total Check													
	MRI Telescope	12.14 kg	0.00 W											



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

Deep Impact - Report as of 26 March 1999

Summary Costs (Thousands of FY1999 Dollars)

Estimated Costs

#	Project WBS Elements	Level	FY2000	FY2001	FY2002	FY2003	FY2004	FY2005	FY2006	Total
1.0	Project Management / Mission Analysis / System Eng	1	2,041	1,855	2,204	2,268	659	-	-	9,02
2.0	Science Team	1	766	530	688	758	338	-	-	3,08
3.0	Flight System	1	18,174	42,573	37,344	14,786	1,604	-	-	114,48
3.1	Program Management	2	1,247	1,086	1,483	1,449	468	-	-	5,73
3.2	System Engineering	2	892	645	315	11	-	-	-	1,86
3.3	Instruments	2	3,450	13,677	7,635	1,644	255	-	-	26,66
3.3.1	Instrument Management	3	599	1,070	1,525	528	64	-	-	3,78
3.3.2	Instrument Systems Engineering	3	547	763	1,009	799	157			
3.3.3	Instrument Product Assurance	3	104	287	478	194	12			
3.3.4	Telescopes	3	135	859	148	-				
3.3.5	Spectral Camera	3	347	4,476	683	-				
3.3.6	Electronics Module	3	699	3,664	885	-				
3.3.7	Instrument Software	3	857	771	388	95	22			
3.3.8	HRI	3	50	267	609	-				
3.3.9	MRI	3	63	271	536	-				
3.3.A	Impactor Target Sensor	3	49	331	763	27				
3.3.B	Ground Support Equipment	3	-	918	610	-				
3.4	Flyby Spacecraft	2	9,680	19,920	20,526	7,032	717			
3.4.1	Program Management	3	2,179	1,848	2,834	2,323	39			
3.4.2	System Engineering	3	830	781	852	458	118			
3.4.3	Product Assurance	3	425	542	703	513				
3.4.4	Propulsion	3	403	1,454	1,096	186	197			
3.4.5	Telecommunications	3	723	2,678	1,826	424	5			
3.4.6	Electrical Power	3	644	3,192	2,049	304	5			
3.4.7	Structure	3	764	2,720	3,411	239				
3.4.8	C&DH	3	608	3,688	2,527	750				
3.4.9	ADCS	3	439	977	2,071	489				
3.4.A	Thermal	3	269	445	766	193				
3.4.C	Software	3	2,037	704	679	-				
3.4.D	Integration & Test	3	75	212	1,035	897				
3.4.E	Ground Support Equipment	3	285	678	677	256				
3.5	Impactor	2	2,905	7,245	7,385	2,909	29			
3.6	Deep Impact Integration & Test	2	-	-	-	1,741	136			
3.6.1	System Integration & Test Management	3	-	-	-	284	2			
3.6.2	Flyby S/C and Impactor Integration & Test	3	-	-	-	1,035	114			
3.6.3	System MGSE	3	-	-	-	172				
3.6.4	System EGSE	3	-	-	-	250				
4.0	Launch Site & Orbital Operations	1	86	140	243	422	783			
4.1	Pre Launch Planning	2	86	140	243	237	67			
4.2	Launch Site Support	2	-	-	-	185	606			
4.4	Flight Operations	2	-	-	-	-	109			
5.0	Pre-Launch GDS/MOS Development	1	398	391	1,187	2,959	978			
6.0	Mission Operations and Data Analysis	1	-	-	-	-	3,47			
6.1	Mission Operations	2	-	-	-	-	1,572			
6.1.3	Phase E Mission Operations	3	-	-	-	-	1,572			
6.2	Science Team	2	-	-	-	-	1,899			
7.0	Deep Space Network (DSN) or Other Tracking Servic	1	-	-	-	-	-			
8.0	Education and Public Outreach	1	636	419	606	779	993			
10.0	Launch Services	1	-	-	-	-	-			
	Subtotal		22,101	45,909	42,272	21,972	8,826			
	Total JPL Reserves		541	11,660	12,432	5,813	2,109			
	Total		22,642	57,569	54,704	27,785	10,935			
	ELV and Launch Services		-	11,465	21,001	14,388	8,243			
	DSN and Tracking Support		-	-	-	-	779			
	TOTAL NASA COST		22,642	69,034	75,705	42,173	19,957			
	Ball Aerospace Contribution		500	500	1,325	825				
33.0	Flight System	1	500	500	1,325	825				
33.3	Instruments	2	500	-	-	-				
33.3.7	Software	3	500	-	-	-				
33.5	Impactor	2	-	500	975	525				
33.5.E	Ground Support Equipment	3	-	500	975	525				
33.6	Deep Impact Integration & Test	2	-	-	350	300				

Summary Costs (Thousands of FY1999 Dollars)

Estimated Costs

NASA WBS Elements	Level	FY2000	FY2001	FY2002	FY2003	FY2004	FY2005	FY2006	Total
Deep Impact	1	22,642	69,034	75,705	42,173	19,957	8,709	1,634	239,854
Project Management	2	680	618	735	756	220	-	-	3,009
Systems Engineering	2	680	618	735	756	220	-	-	3,009
Safety and Mission Assurance	2	680	618	735	756	220	-	-	3,009
Science/Technology	2	766	530	688	758	2,237	3,111	1,105	9,195
Payload(s)	2	3,450	13,677	7,635	1,644	255			
Payload Management	3	599	1,070	1,525	528	64			
System Engineering	3	547	763	1,009	799	157			
Payload Product Assurance	3	104	287	478	194	12			
HRI	3	737	4,308	1,018	32	7			
HRI Management	4								
HRI Systems Engineering	4								
HRI Assurance	4								
Antenna	4								
Optics	4	45	286	49	-	-			
Sensors/Detectors	4	173	2,238	341	-	-			
Structures & Mechanisms	4								
Thermal Control	4								
Electronics	4	233	1,221	295	-	-			
Power	4								
Pointing Subsystem	4								
Harness & Cabling	4								
C&DH	4	286	257	129	32	7			
Ground Support Equip	4	-	306	203	-	-			
MRI	3	737	4,308	1,018	32	7			
ITS	3	564	2,071	677	32	7			
Integration, Assembly Test & Check out	3	162	870	1,909	27	-			
Flight System \ Spacecraft	2	14,725	28,896	29,709	11,401	1,213			
Launch Vehicle/Services	2	-	11,465	21,001	14,388	8,243			
Mission Operations System (MOS)	2	199	196	593	1,480	2,061	2,31		
Ground Data System (GDS)	2	199	196	593	1,480	1,268	1,15		
System Integration, Assembly, Test & Check Out	2	86	140	243	2,163	918			
Education & Public Outreach	2	636	419	606	779	993	74		
Reserves	2	541	11,660	12,432	5,813	2,109	1,39		
Corporate G&A	1								
Center Management Operations (CMO)	1								

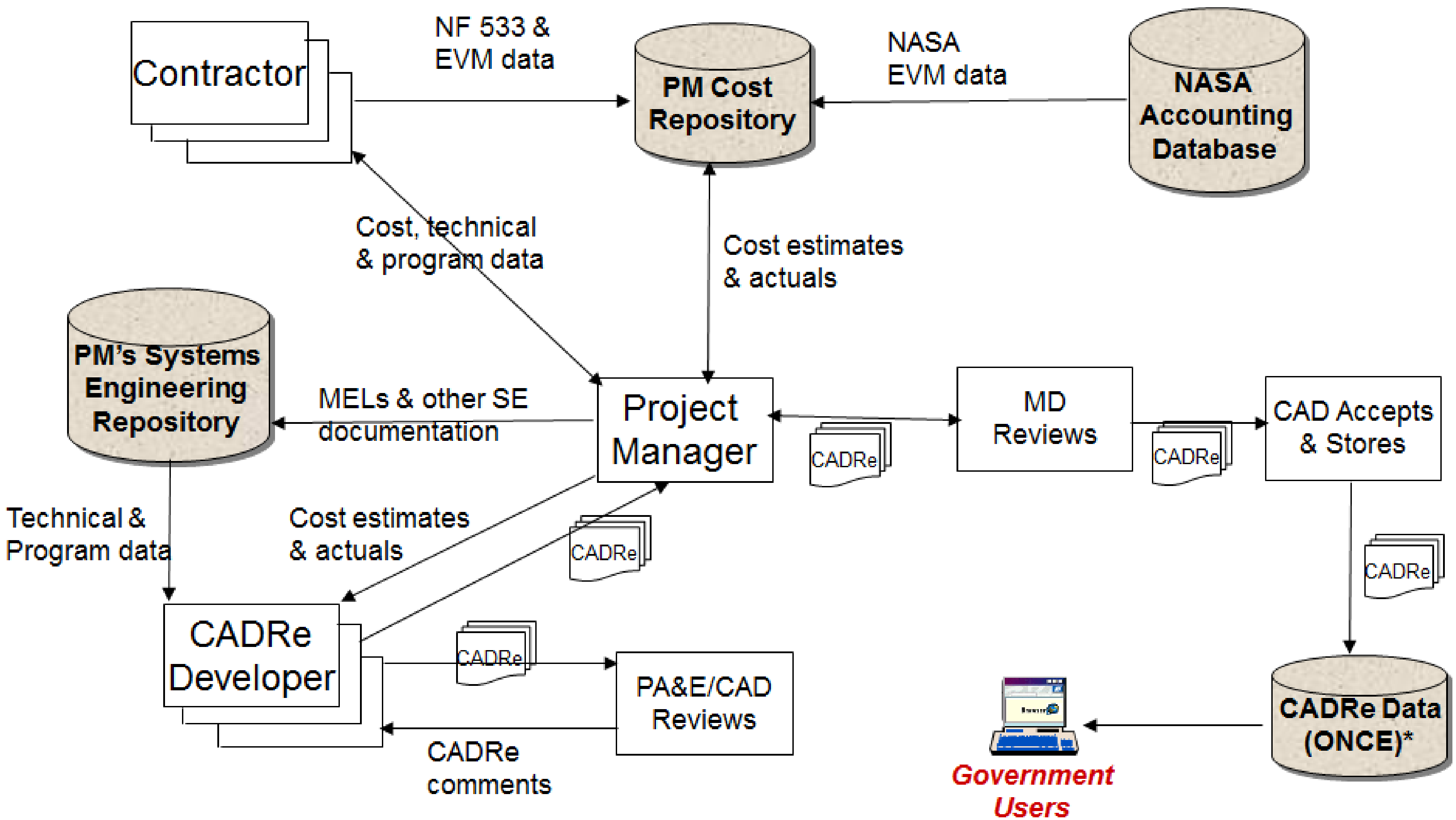
WBS #	WBS Element Name	Lev	Description of inclusions and exclusions
10000	Project Management/Mission Analysis/System En	1	
11000	Project Management	2	Includes responsibility for the overall mission implementation. This includes all efforts associated with project level planning and control, directing subcontractor efforts and interactions, as well as
12000	Project & Mission Engineering	2	Includes the project-level engineering required to ensure that all satellite subsystems and payloads function properly to achieve system goals and requirements. This also includes the data/report generation activities required to produce internal and deliverable documentation. Includes
13000	Safety and Mission Assurance Management	2	Includes all efforts associated with the development and implementation of the Project's Mission Assurance program throughout Phases A/B. This includes the identification and control of Project technical risks, preparing the Mission Assurance Plan and providing overview of the mission
14000	Launch Vehicle Coordination	2	Includes the coordination and procurement of launch vehicles and services from KSC. This includes procurement of the ELV, spacecraft-to-launch vehicle integration, placement of spacecraft into designated orbit, analysis, post-flight mission data evaluation, oversight of the launch service and
20000	Science Team	1	
21000	Principal Investigator/Science Management	2	Includes all costs for the PI's time except for time spent on the ST4/Champollion Liaison. It includes the percentage devoted to EPO (WBS 81000), to the target characterization observing and
22000	Target Characterization	2	Includes characterization of the target prior to impact, carrying out the observations, reducing the data, and analyzing the data sufficiently to determine the parameters that are relevant to the
23000	Encounter/Earth-Based Campaign	2	Combined Into 22000
24000	Laboratory Cratering Studies	2	Includes studying the cratering process, both in the laboratory and via numerical simulation.
25000	ST-4 Liaison	2	Includes the efforts of the PI and Deputy PI in carrying out liaison with the ST4/Champollion
26000	Data Analysis	2	This element is not used in Phase A/B since the analysis of the data from the target
27000	Data Processing/Software	2	Includes the modification of software for processing the data at the Cornell Science Data Center and the costs of installing a suitable subset of that software at JPL for near-real-time display of
28000	Data Archiving	2	Includes archiving the data into the PDS. In Phase A/B it includes mainly the preparation of the Archiving plan, determination of the archival products to be included in the archive, preliminary design of PDS labels and volumes, assembling associated archival documentation, and preliminary
29000	Science Planning	2	Includes planning for optimizing the total return from the mission, simulations for the mission, analysis of data either from the literature or from the Earth-based observing programs, reviewing
30000	Flight System	1	
31000	Program Management	2	Includes the management of the flight system development and program liaison with the support functions of system engineering, product assurance, fabrication, subcontract and material
32000	System Engineering	2	Includes the technical management of the flight system subsystem and mission including design,
33000	Instruments	2	
34000	Flyby Spacecraft	2	
35000	Impactor	2	
36000	Deep Impact Integration and Test	2	Planning effort only in Phase A/B.
40000	Launch Site and Orbital Operations	1	Includes initial planning and coordination of launch vehicle, launch site, and mission operations
41000	Pre-Launch Planning	2	
42000	Launch Site Support	2	
43000	Launch Vehicle Integration	2	
44000	Flight Operations	2	
50000	Pre-Launch GDS/MOS Development	1	
51000	Management, System Engineering, and I&T	2	Includes management of resources to deliver a system to operate the DI mission. This includes operations system configuration management, software development, product assurance, and make/buy decisions, negotiation of management agreements with members of operations system
52000	JPL	2	Includes acquisition, installation, and maintenance of operations computers at JPL, including mission support area facilities. Includes mission planning and analysis, scheduling of multimission services and sequence integration and verification. Includes training Ball personnel on the use of
53000	Ball	2	N/A to Phase A/B.
60000	Mission Operations & Data Analysis	1	N/A Phase A/B
61000	Mission Operations	2	
62000	Science Team	2	
70000	Deep Space Network (DSN) or Other Tracking Ser	1	N/A to Phase A/B.
80000	Education and Public Outreach	1	Includes communicating the mission's progression, scientific investigations, and new discoveries to the broadest possible public audience. Includes using the Amateur Astronomer's Network, bringing the public to the telescope, a Planetarium show, the World Wide Web, news media, and distribution
81000	University of Maryland	2	
82000	Ball	2	
83000	JPL	2	
90000	Project Unique Facilities	1	The project will require no construction or lease of any ground facilities.
91000	University of Maryland	2	
92000	Ball	2	
93000	JPL	2	
100000	Launch Services	1	N/A to Phase A/B.
A1000	Launch Vehicle	2	
A2000	Propellants	2	

Lifecycle Cost Estimate

Costs Mapped to the NASA WBS

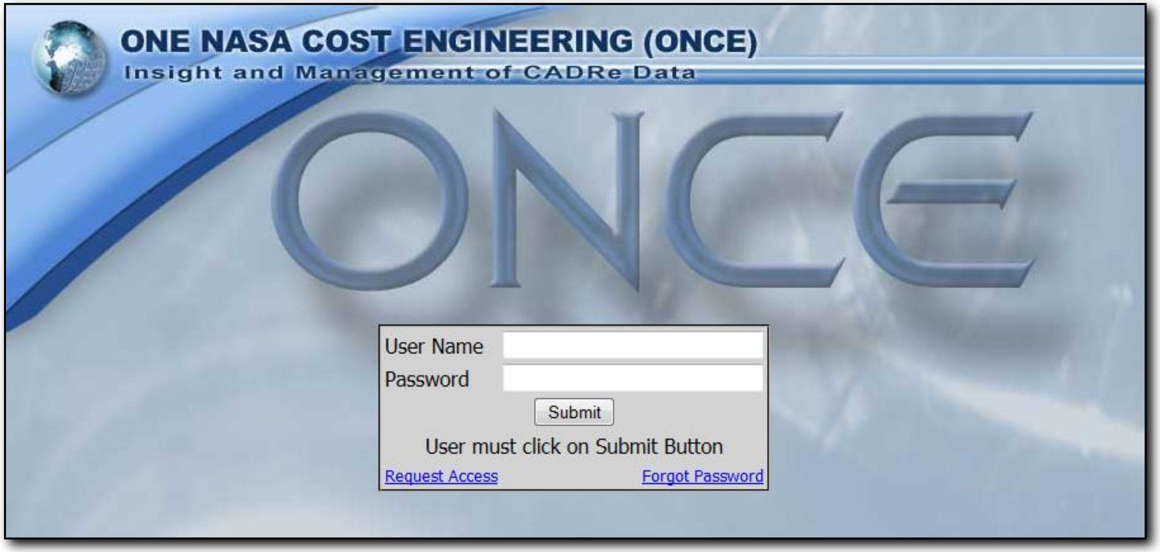
WBS Dictionary

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

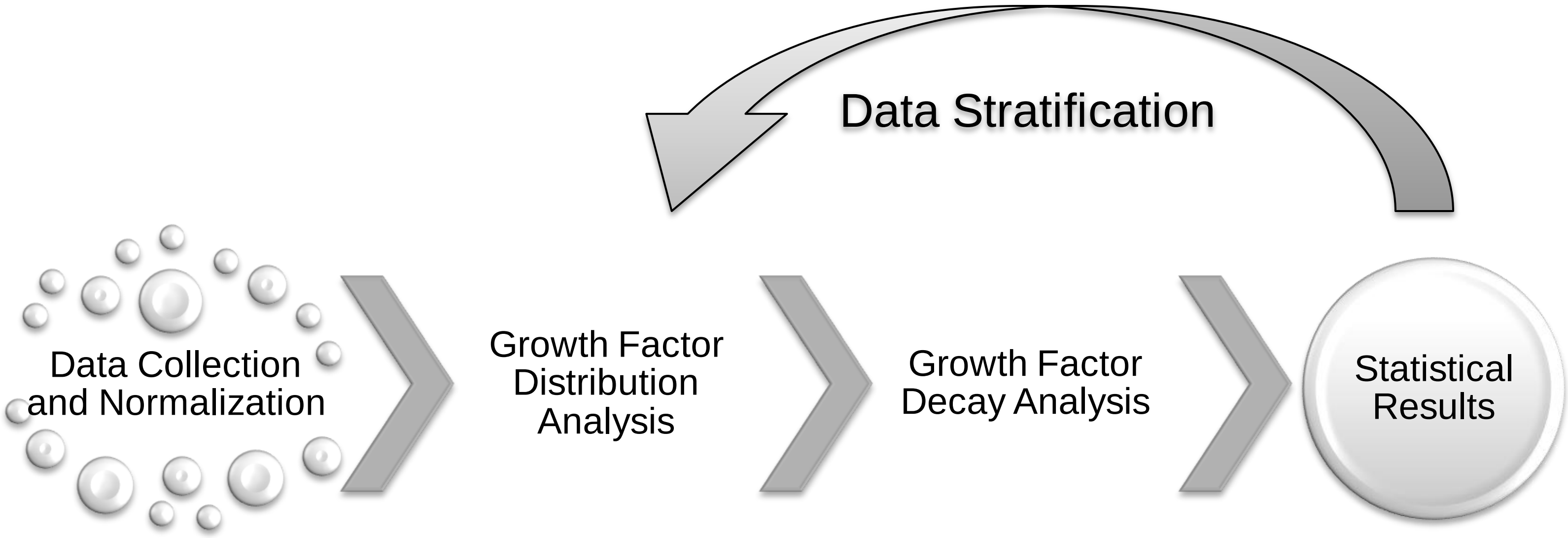
- As the project nears the launch milestone, mass estimates increase in accuracy
  - Mean of the mass values by milestone approaches 1 (zero growth) – Getting better at predicting Launch Mass
  - Standard Deviation decreases as the mass technical baseline matures – Lower variability in mass range
- An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

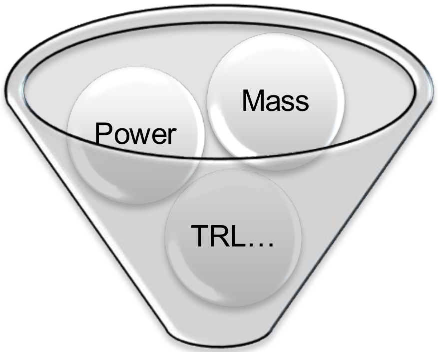
Study Process



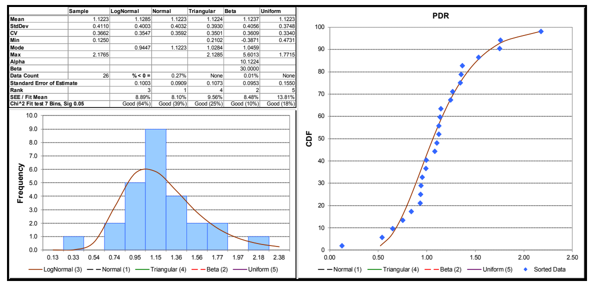
- Assessment and evaluation of source data, extraction, normalization, and format conducted prior to data analysis
- Statistical Analysis software facilitates Growth Factor and Decay analysis – used COTS tools (Excel and CO$TAT from ACEIT Software suite)
- Data Stratifications include selection of Milestone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

Analysis Framework

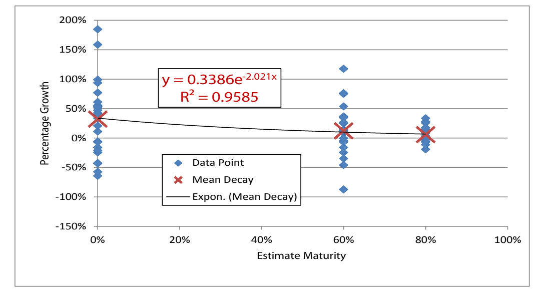
Data Collection

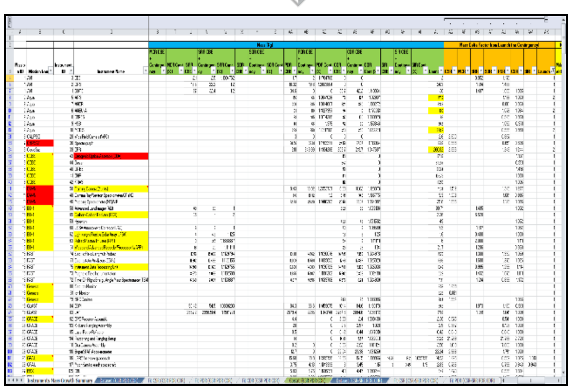


Growth Factor Analysis



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	0.994652406
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

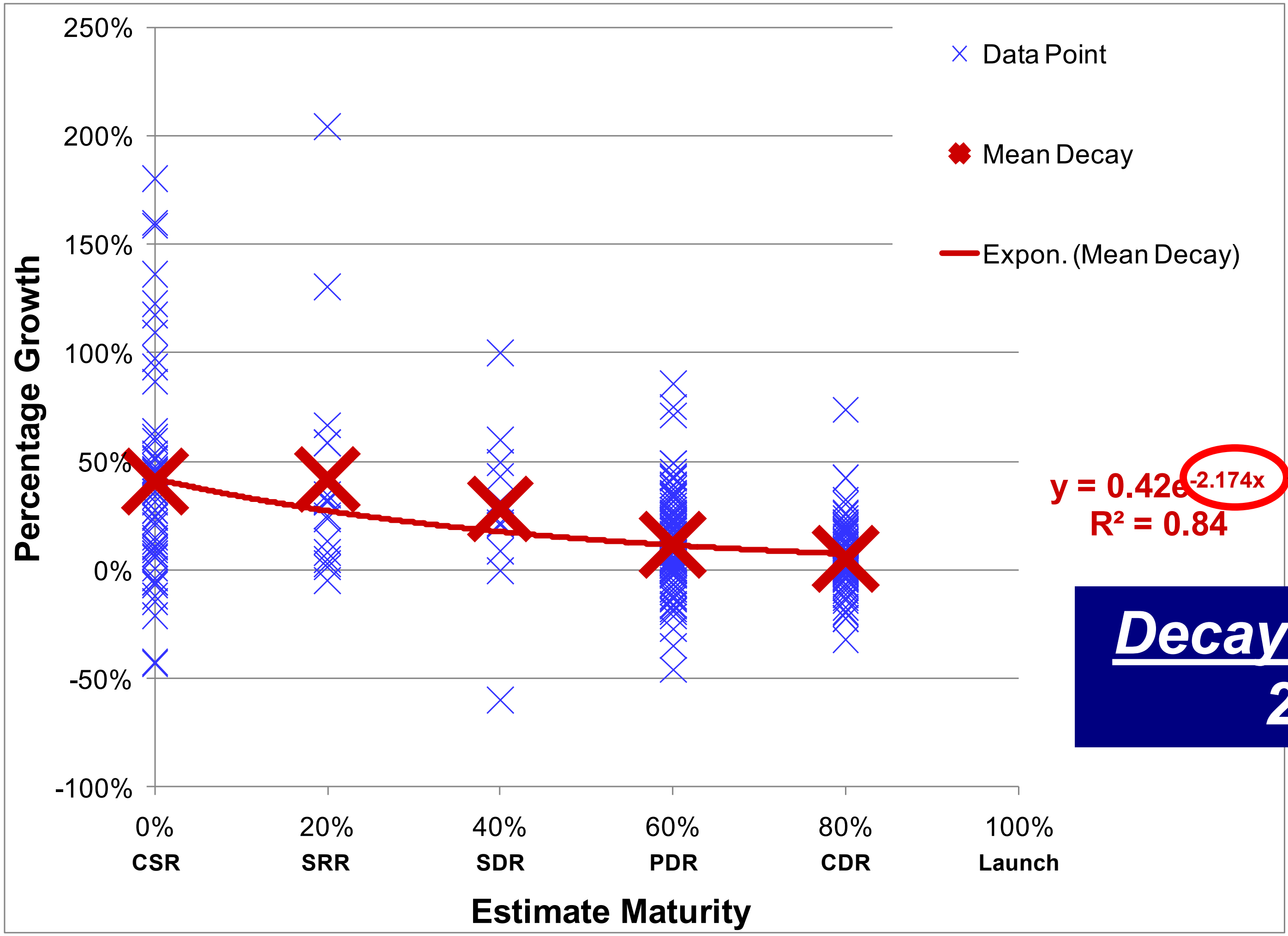
b = Mass Growth Decay Constant

t = Estimate Maturity Parameter

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

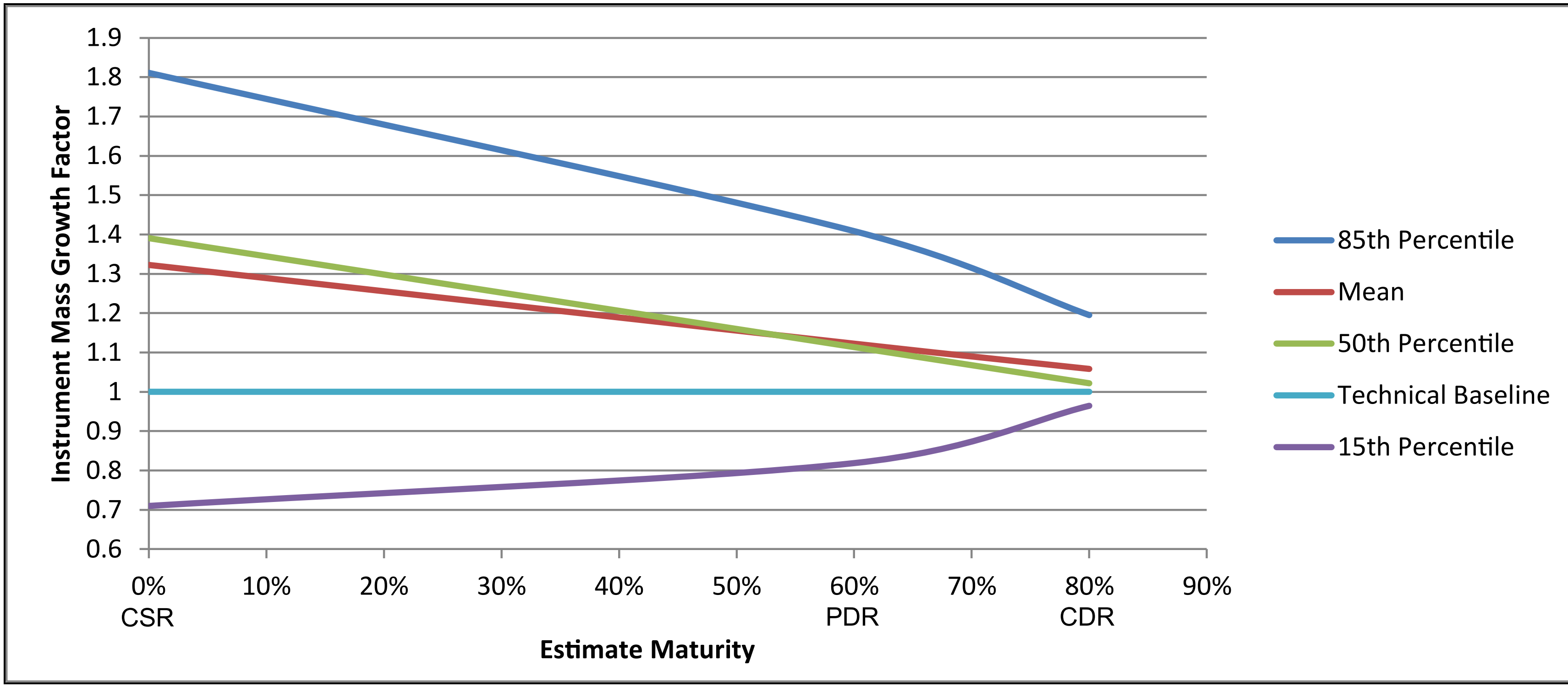
Enables Analysts to Use at any Point in Design Cycle and not just at Milestones

Deriving a Decay Constant from Mass Growth Data



Decay Constant
2.174

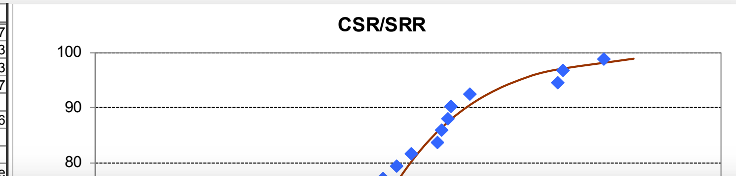
Example of Continuous Mass Growth Decay Model

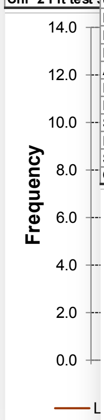


Enhances Analyst Capability to Specify Mass Uncertainty Ranges for CERs and SERs

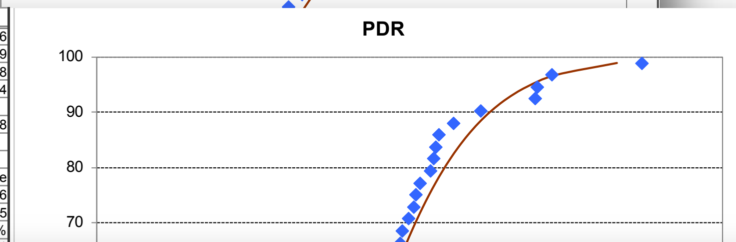
Mass Growth Distributions
Common Milestones – CADRe Data

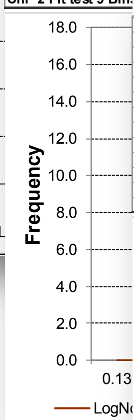
	Sample	LogNormal	Normal	Triangular	Beta	Uniform
Mean	1.3787	1.3853	1.3787	1.3788	1.3800	1.3787
StdDev	0.5359	0.5269	0.5272	0.5210	0.5309	0.5023
CV	0.3887	0.3804	0.3824	0.3779	0.3847	0.3643
Min	0.3571			0.2284	-0.0626	0.5087
Mode	1.5357	1.1312	1.3787	1.1564	1.2101	
Max	2.8462			2.7515	8.5258	2.2486
Alpha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



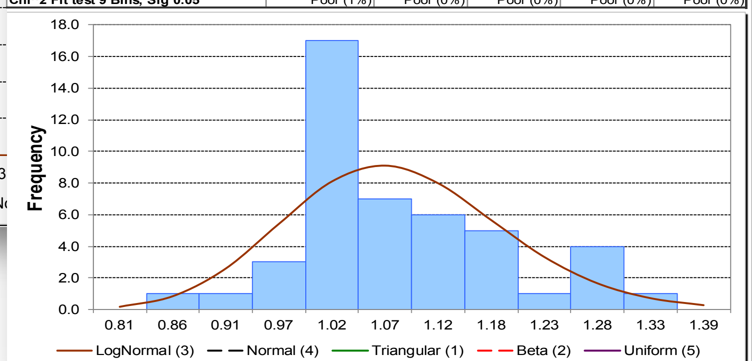


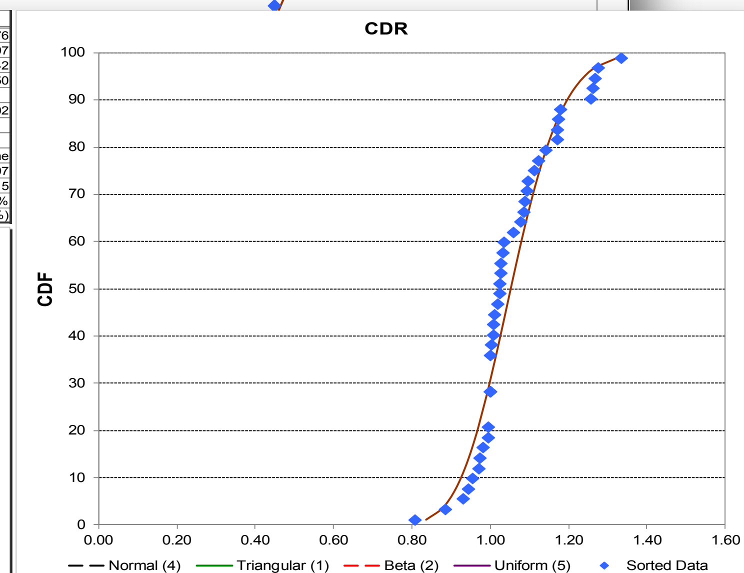
	Sample	LogNormal	Normal	Triangular	Beta	Uniform
Mean	1.1426	1.1447	1.1426	1.1426	1.1430	1.1426
StdDev	0.3350	0.3225	0.3226	0.3144	0.3219	0.2969
CV	0.2932	0.2817	0.2823	0.2751	0.2816	0.2598
Min	0.1250			0.4140	-0.1470	0.6284
Mode		1.0208	1.1426	1.0655	1.0896	
Max	2.1765			1.9483	4.5181	1.6568
Alpha					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 (10%)	Poor (2%)	Poor (1%)	Poor (2%)





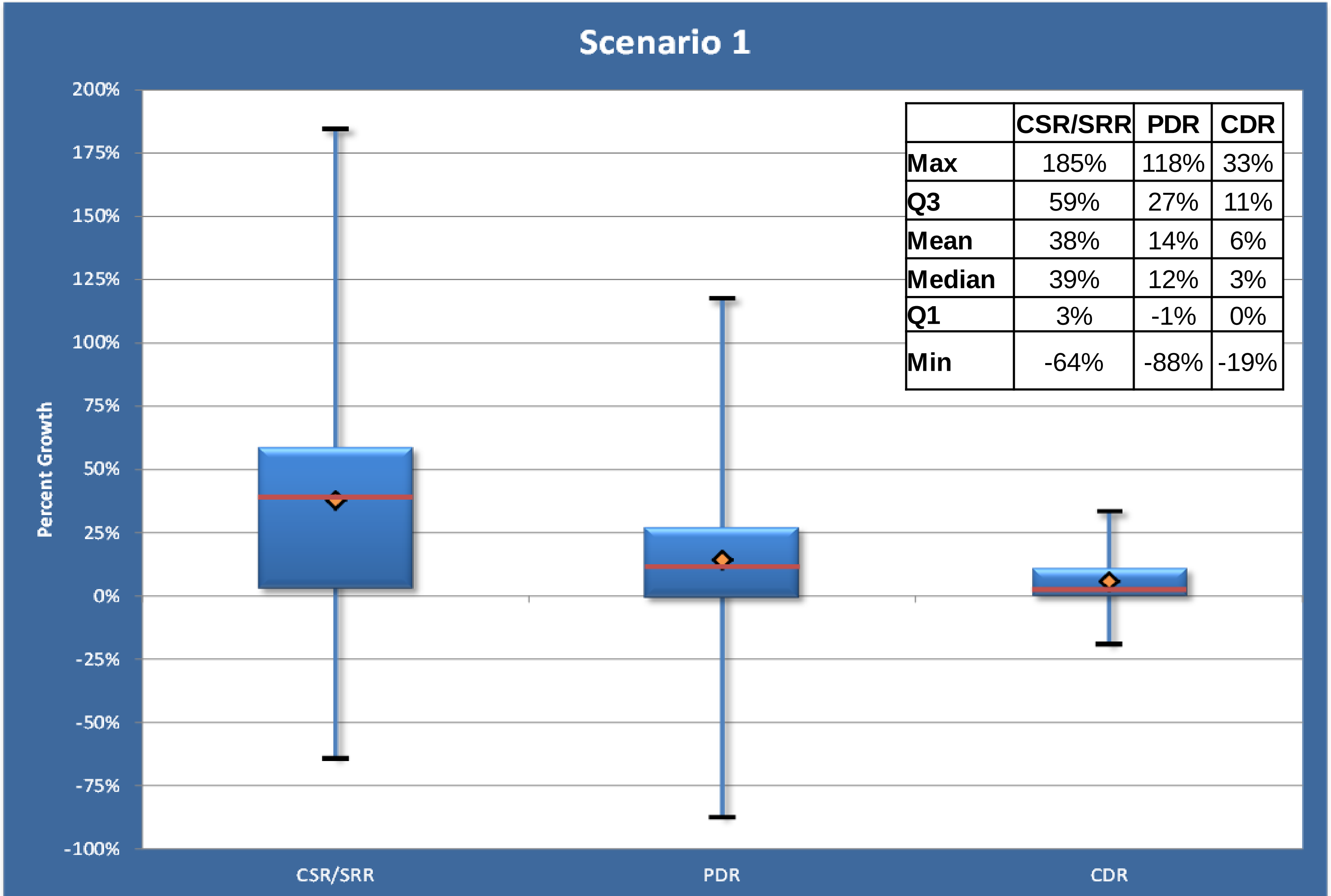
	Sample	LogNormal	Normal	Triangular	Beta	Uniform
Mean	1.0576	1.0576	1.0575	1.0576	1.0578	1.0576
StdDev	0.1080	0.1062	0.1044	0.1043	0.1048	0.0997
CV	0.1021	0.1004	0.0987	0.0986	0.0991	0.0942
Min	0.8085			0.8526	0.9046	0.8850
Mode	1.0000	1.0418	1.0575	0.9764	0.9667	
Max	1.3341			1.3439	1.5016	1.2302
Alpha					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%)





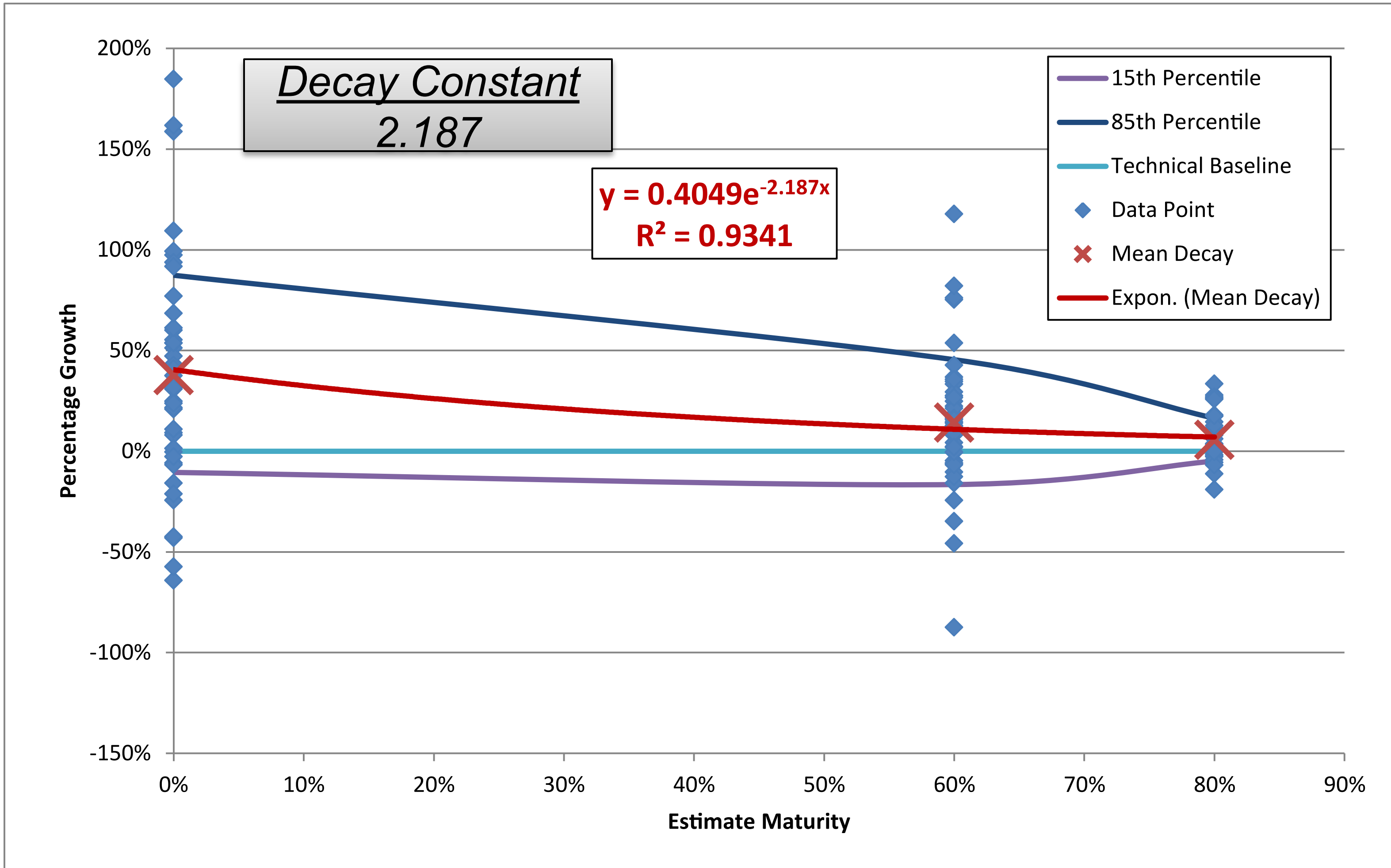
Percent Growth by Milestone

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%

Products

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