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.

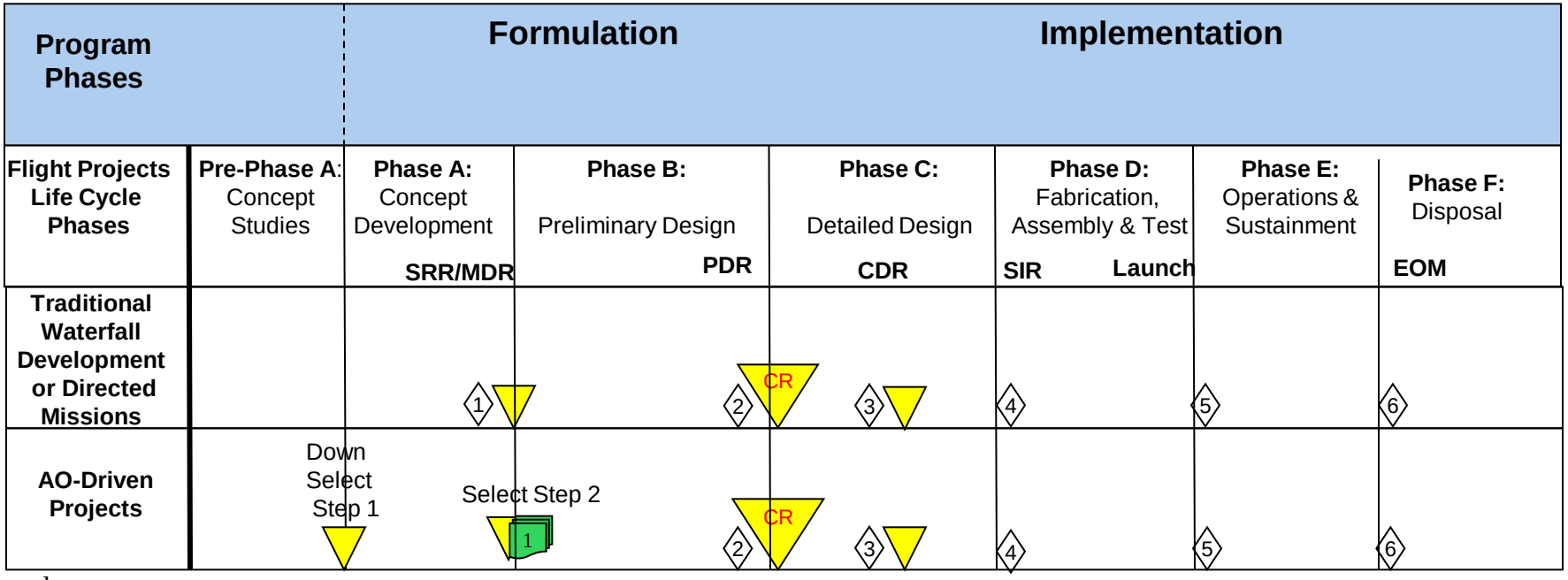
Background

- 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

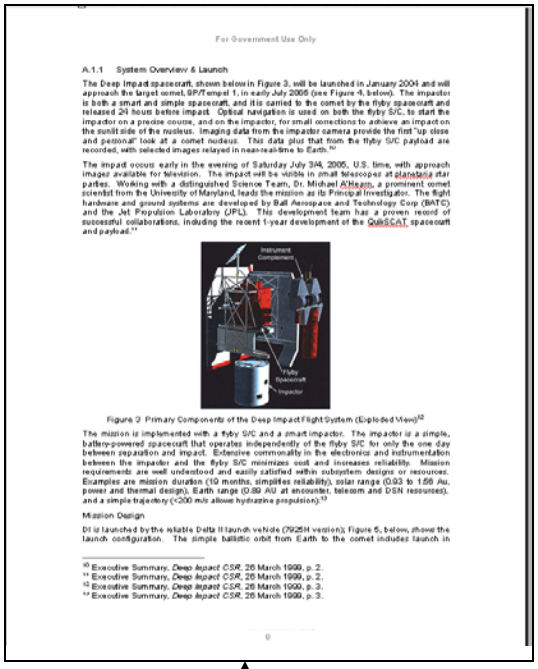


Legend

- 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 3rd, 2005, U.S. time, with approach imagery 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]

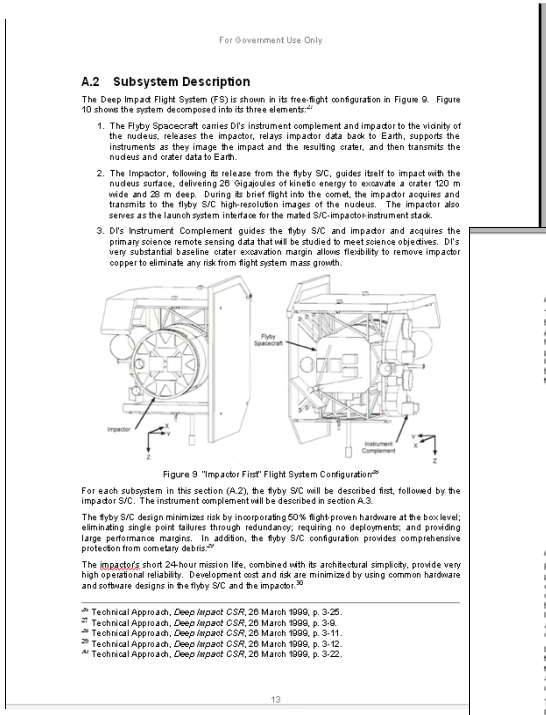
Figure 3 Primary Components of the Deep Impact Flight System (Exploded View)[12]

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 (10 months, simplifies reliability), solar range (0.93 to 1.58 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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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:[21]

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.

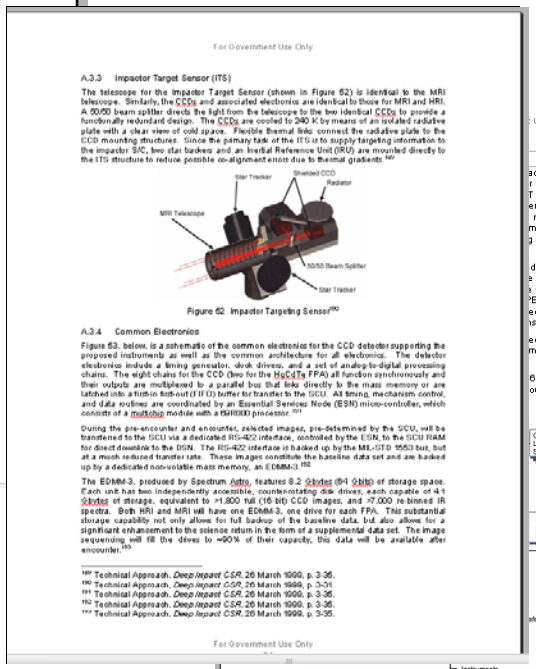
Figure 9 "Impactor First" Flight System Configuration[22]

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.[23]

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]

[21] Technical Approach, *Deep Impact CSR*, 26 March 1999, p. 3-25.
[22] Technical Approach, *Deep Impact CSR*, 26 March 1999, p. 3-9.
[23] 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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A.3.3 Impactor Target Sensor (ITS)

The telescope for the Impactor Target Sensor (shown in Figure 62) is identical to the MRI telescope. Similarly, the CCDs and associated electronics are identical to those for MRI and HRI. A 50/50 beam splitter directs the light from the telescope to the two identical CCDs to provide a functionally redundant design. The CCDs are cooled to 240 K by means of an isolated radiative plate with a clear view of cold space. Flexible thermal links connect the radiative plate to the CCD mounting structures. Since the primary task of the ITS is to supply targeting information to the impactor S/C, two star trackers and an Inertial Reference Unit (IRU) are mounted directly to the ITS structure to reduce possible co-alignment errors due to thermal gradients.[190]

Figure 62 Impactor Targeting Sensor[190]

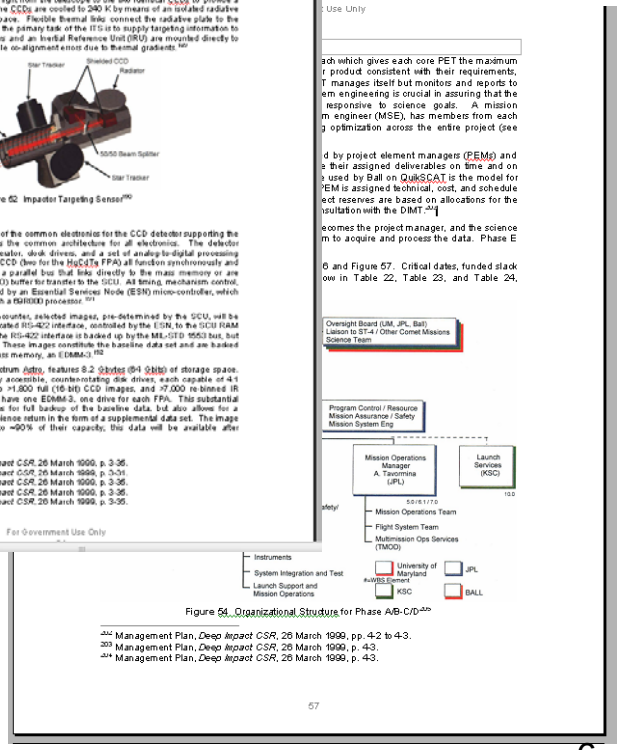
A.3.4 Common Electronics

Figure 63, below, is a schematic of the common electronics for the CCD detector supporting the proposed instruments as well as the common architecture for all electronics. The detector electronics include a timing generator, clock drivers, and a set of analog-to-digital processing chains. The eight chains for the CCD (two for the HuCdTe FPA) all function synchronously and their outputs are multiplexed to a parallel bus that links directly to the mass memory or are latched into a first-in first-out (FIFO) buffer for transfer to the SCU. All timing, mechanism control, and data routines are coordinated by an Essential Services Node (ESN) micro-controller, which consists of a multichip module with a RS6000 processor.[191]

During the pre-encounter and encounter, selected images, pre-determined by the SCU, will be transferred to the SCU via a dedicated RS-422 interface, controlled by the ESN, to the SCU RAM for direct downlink to the DSN. The RS-422 interface is backed up by the MIL-STD 1553 bus, but at a much reduced transfer rate. These images constitute the baseline data set and are backed up by a dedicated non-volatile mass memory, an EDMM-3.[192]

The EDMM-3, produced by Spectrum Astro, features 8.2 Gbytes (64 Gbits) of storage space. Each unit has two independently accessible, counter-rotating disk drives, each capable of 4.1 Gbytes of storage, equivalent to >1,800 full (16-bit) CCD images, and >7,000 re-binned IR spectra. Both HRI and MRI will have one EDMM-3, one drive for each FPA. This substantial storage capability not only allows for full backup of the baseline data, but also allows for a significant enhancement to the science return in the form of a supplemental data set. The image requencing will fill the drives to ~90% of their capacity, this data will be available after encounter.[193]

[189] Technical Approach, *Deep Impact CSR*, 26 March 1999, p. 3-36.
[190] Technical Approach, *Deep Impact CSR*, 26 March 1999, p. 3-31.
[191] Technical Approach, *Deep Impact CSR*, 26 March 1999, p. 3-36.
[192] Technical Approach, *Deep Impact CSR*, 26 March 1999, p. 3-36.
[193] Technical Approach, *Deep Impact CSR*, 26 March 1999, p. 3-35.



ach which gives each core PET the maximum
r product consistent with their requirements,
T manages itself but monitors and reports to
em engineering is crucial in assuring that the
responsive to science goals. A mission
m engineer (MSE), has members from each
g optimization across the entire project (see

d by project element managers (PEMs) and
their assigned deliverables on time and on
used by Ball on QuikSCAT is the model for
EM is assigned technical, cost, and schedule
ect reserves are based on allocations for the
sultation with the DIMT.[202]

ecomes the project manager, and the science
m to acquire and process the data. Phase E

6 and Figure 57. Critical dates, funded slack
ow in Table 22, Table 23, and Table 24,

Oversight Board (UM, JPL, Ball)
Liaison to ST-4 / Other Comet Missions
Science Team

Program Control / Resource
Mission Assurance / Safety
Mission System Eng

Mission Operations Manager
A. Tavormina
(JPL)

Launch Services
(KSC)

Mission Operations Team
Flight System Team
Multimission Ops Services (TMOD)

Instruments
System Integration and Test
Launch Support and Mission Operations

University of Maryland
JPL
KSC
BALL

Figure 54 Organizational Structure for Phase A/B-C/D[203]

[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.

System Overview

Subsystem Description

Payload Description

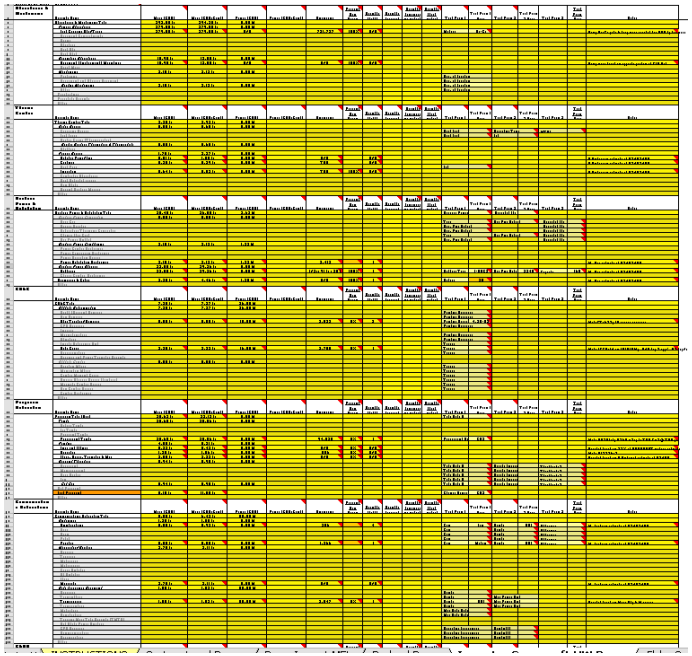
Project Management

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: MIR	High Resolution Instrument	Contractor				
Instrument 2: MIR	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	100.41kg	75.95W											
Instrument 1:	Total	51.26kg	32.75W											
	Optics	8.39kg	4.00W											
	Sensors/Detectors	2.06kg	0.00W					Type		Pixel Size				
	Structural & Mechanical	24.79kg	0.00W											
	Thermal Control	2.47kg	0.00W											
	Electronics	10.07kg	20.75W											
	Power							Peak Power		Duty Cycle				
	Painting Subsystem													
	Harness, Cabling, etc.	2.28kg	0.00W	TBD			AR							
	C&DH							Peak Data Rate		Duty Cycle				
	Other													
Instrument 2:	Total	29.11kg	32.75W											
	Optics	5.01kg	4.00W											
	Optics [MRI Telescope]	0.32kg	0.00W				1	Diameter (	10	Focallens	2.1	F/#	21	Al Coated Zerodur
	Optics [MRI Spectral Imaging Module]	1.67kg	0.00W	various			10							Diamond Turned Al, Prisms, Filters
	Scan Mirror [MRI Spectral Imaging Module]	0.32kg	0.50W	512		0%	1							BSH 20-20-0
	Filter Wheel [MRI Spectral Imaging Module]	2.49kg	3.50W	3,434		0%	1							ACS Small Filter wheel, Motor-Cube-C
	Sensors/Detectors	2.06kg	0.00W					Type		Pixel Size				
	CCD Structure (incl. CCD) [MRI Spectral Imaging Module]	0.55kg	0.00W	600			1	Type		Pixel Size	21			9-stage 2K x 1K Split Frame Transfer
	Radiation Cooler (incl. IR FPA) [MRI Spectral Imaging Mo	2.51kg	0.00W	9,017		0%	1	Type		Pixel Size	37			TCH5000
	Structural & Mechanical	17.17kg	0.00W											
	Structure [MRI Telescope]	0.76kg	0.00W	3,242			1							GFE Tube
	Structure, Baffling, Cover [MRI Spectral Imaging Module]	13.96kg	0.00W	84,000			AR							Al honeycomb bench
	Optics Mounts [MRI Spectral Imaging Module]	1.67kg	0.00W	various			10							
	Kinematic Mounts [MRI Spectral Imaging Module]	0.76kg	0.00W	TBD			3							
	Thermal Control	1.52kg	0.00W											
	MLI [MRI Telescope]	0.12kg	0.00W	TBD			AR							
	MLI [MRI Spectral Imaging Module]	1.40kg	0.00W	TBD			AR							
	Electronics	10.07kg	20.75W											
	Boards and Chassis [MRI Common Electronics]	5.24kg	10.75W	4,500			1							
	Erasable Mass Memory [MRI Common Electronics]	4.83kg	10.00W	6,250			1							EDMM-3
	Power							Peak Power		Duty Cycle				
	Painting Subsystem													
	Harness, Cabling, etc.	2.28kg	0.00W	TBD			AR							
	C&DH							Peak Data Rate		Duty Cycle				
	Other													
Instrument 3:	Total	10.04kg	10.35W											
	Optics	0.37kg	0.00W											
	Optics [MRI Telescope for ITS]	0.32kg	0.00W				1	Diameter (	10	Focallens	2.1	F/#	21	Al Coated Zerodur
	Beam Splitter [ITS]	0.05kg	0.00W	6			1							50/50
	Sensors/Detectors	1.09kg	0.00W	600			2	Type		Pixel Size	21			9-stage 2K x 1K Split Frame Transfer
	Structural & Mechanical	5.06kg	0.00W											
	Structure [MRI Telescope for ITS]	0.76kg	0.00W	3,242			1							GFE Tube
	Structure, Baffling, Cover, Rack [ITS]	3.35kg	0.00W	12,000			1							Incl. mounts for Star Trackers and IRU
	Kinematic Mounts [ITS]	0.52kg	0.00W	TBD			3							
	Thermal Control	0.36kg	0.00W											
	MLI [MRI Telescope for ITS]	0.12kg	0.00W	TBD			AR							
	MLI [ITS]	0.24kg	0.00W	TBD			AR							
	Electronics	0.58kg	1.35W	TBD			AR							
	Power							Peak Power		Duty Cycle				
	Painting Subsystem													
	Harness, Cabling, etc.	2.98kg	9.00W	2,700			1							
	C&DH							Peak Data Rate		Duty Cycle				
	Other													
	Total Check													
	MRI Telescope	12.14kg	8.00W											



System Level Tables

Payload Level Tables

Summary Tables

SYSTEM SUMMARY TABLE

	CBE Mass	CBE Mass w/Contingene	CBE Power	CBE Power w/Contingene
Payload Mass	**89.4 kg**	**100.4 kg**	**75.9 W**	
Instrument 1 (MIR)	45.6 kg	51.3 kg	32.8 W	
Instrument 2 (MIR)	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	7.2 kg	26.0 W	
Propulsion Dry Mass	30.6 kg	32.1 kg	5.0 W	
Telecommunications	5.9 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	196.0 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

VIS 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)	64.0
	GNSC 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 (BPV)
	Battery Power Output	15 A-hr
Propulsion Subsystem	Monopropellant Thrusters Thrust	2.2 N (16 PICS), 25 N (4)
	Propellant Type	N2H4
Telecommunications Subsystem	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)

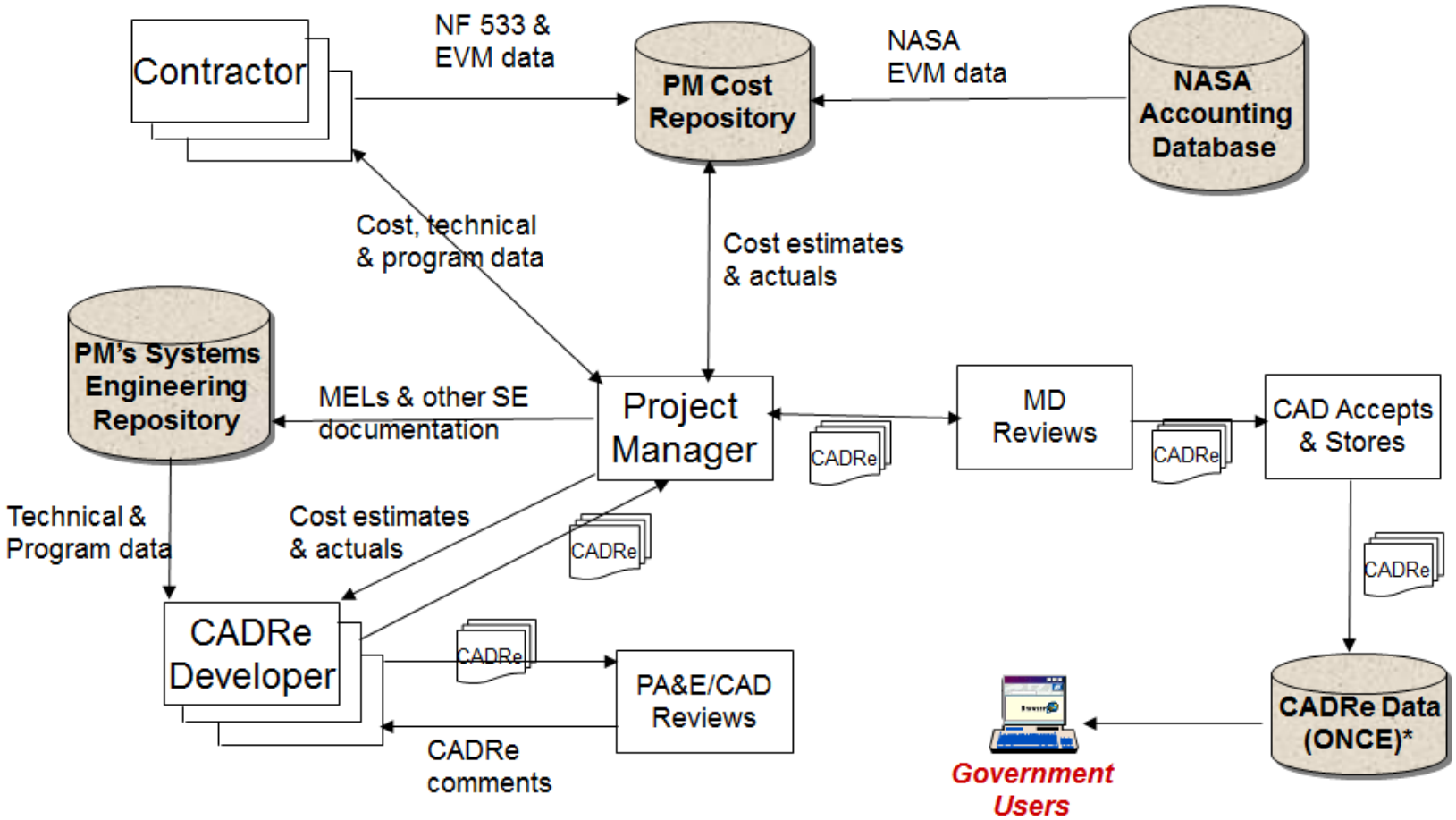
#	Project WBS Elements	Level	FY2000	FY2001	FY2002	FY2003	FY2004	FY2005	FY2006	Total
			Estimated Costs							
1.0	Project Management / Mission Analysis / System Eng	1	2,041	1,855	2,204	2,268	659	-	-	9,02
2.0	Science Team	1	766	530	688	758	338	-	-	3,08
3.0	Flight System	1	18,174	42,573	37,344	14,786	1,604	-	-	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	-	-	3,27
3.3.3	Instrument Product Assurance	3	104	287	478	194	12	-	-	1,07
3.3.4	Telescopes	3	135	859	148	-	-	-	-	1,14
3.3.5	Spectral Camera	3	247	4,476	693	-	-	-	-	5,50
3.3.6	Electronics Module	3	699	3,664	885	-	-	-	-	5,24
3.3.7	Instrument Software	3	857	771	388	95	22	-	-	2,13
3.3.8	HRI	3	50	267	609	-	-	-	-	92
3.3.9	MRII	3	63	271	536	-	-	-	-	87
3.3.A	Impactor Target Sensor	3	49	331	763	27	-	-	-	1,17
3.3.B	Ground Support Equipment	3	-	918	610	-	-	-	-	1,52
3.4	Flyby Spacecraft	2	9,630	19,920	20,526	7,032	717	-	-	57,87
3.4.1	Program Management	3	2,179	1,848	2,834	2,323	391	-	-	9,57
3.4.2	System Engineering	3	830	781	852	458	118	-	-	3,03
3.4.3	Product Assurance	3	425	542	703	513	-	-	-	2,18
3.4.4	Propulsion	3	403	1,454	1,096	186	197	-	-	3,33
3.4.5	Telecommunications	3	723	2,678	1,826	424	5	-	-	5,65
3.4.6	Electrical Power	3	644	3,192	2,049	304	5	-	-	6,19
3.4.7	Structure	3	764	2,720	3,411	239	-	-	-	7,13
3.4.8	C&DH	3	608	3,688	2,527	759	-	-	-	7,57
3.4.9	ADCS	3	439	977	2,071	489	-	-	-	3,97
3.4.A	Thermal	3	269	465	766	193	-	-	-	1,67
3.4.C	Software	3	2,037	704	679	-	-	-	-	3,42
3.4.D	Integration & Test	3	75	212	1,035	897	-	-	-	2,21
3.4.E	Ground Support Equipment	3	285	678	677	256	-	-	-	1,89
3.5	Impactor	2	2,905	7,245	7,385	2,909	29	-	-	20,47
3.6	Deep Impact Integration & Test	2	-	-	-	1,741	126	-	-	1,87
3.6.1	System Integration & Test Management	3	-	-	-	284	21	-	-	30
3.6.2	Flyby S/C and Impactor Integration & Test	3	-	-	-	1,035	114	-	-	1,14
3.6.3	System MGSE	3	-	-	-	172	-	-	-	17
3.6.4	System EGSE	3	-	-	-	250	-	-	-	25
4.0	Launch Site & Orbital Operations	1	86	140	243	422	783	-	-	1,67
4.1	Pre Launch Planning	2	86	140	243	237	67	-	-	77
4.2	Launch Site Support	2	-	-	-	185	606	-	-	79
4.4	Flight Operations	2	-	-	-	-	109	-	-	10
5.0	Pre-Launch GDS/MOS Development	1	398	391	1,187	2,959	978	-	-	5,91
6.0	Mission Operations and Data Analysis	1	-	-	-	-	3,471	5,426	1,265	10,16
6.1	Mission Operations	2	-	-	-	-	1,572	2,315	159	4,04
6.1.3	Phase E Mission Operations	3	-	-	-	-	1,572	2,315	159	4,04
6.2	Science Team	2	-	-	-	-	1,899	3,111	1,105	6,11
7.0	Deep Space Network (DSN) or Other Tracking Servic	1	-	-	-	-	-	-	-	-
8.0	Education and Public Outreach	1	636	419	606	779	993	743	232	4,40
10.0	Launch Services	1	-	-	-	-	-	-	-	-
	Subtotal		22,101	45,909	42,272	21,972	8,826	6,169	1,497	148,74
	Total JPL Reserves		541	11,660	12,432	5,813	2,109	1,390	137	34,08
	Total		22,642	57,569	54,704	27,785	10,935	7,559	1,634	182,82
	ELV and Launch Services		-	11,465	21,001	14,388	8,243	-	-	55,09
	DSN and Tracking Support		-	-	-	-	779	1,150	-	1,92
	TOTAL NASA COST		22,642	69,034	75,705	42,173	19,957	8,709	1,634	239,85
	Ball Aerospace Contribution		500	500	1,325	825	-	-	-	3,15
03.0	Flight System	1	500	500	1,325	825	-	-	-	3,15
03.3	Instruments	2	500	-	-	-	-	-	-	50
03.3.7	Software	3	500	-	-	-	-	-	-	50
03.5	Impactor	2	-	500	975	525	-	-	-	2,00
03.5.E	Ground Support Equipment	3	-	500	975	525	-	-	-	2,00
03.6	Deep Impact Integration & Test	2	-	-	350	300	-	-	-	65

Summary Costs (Thousands of FY1999 Dollars)

ents	Level	FY2000	FY2001	FY2002	FY2003	FY2004	FY2005	FY2006	Total
		Estimated Costs							
	1	22,642	69,034	75,705	42,173	19,957	8,709	1,634	239,854
nt	2	680	618	735	756	220	-	-	3,009
ng	2	680	618	735	756	220	-	-	3,009
Assurance	2	680	618	735	756	220	-	-	3,009
y	2	766	530	688	758	2,237	3,111	1,105	3,195
	2	3,450	13,677	7,635	1,644	255	-	-	26,661
ment	3	599	1,070	1,525	528	64	-	-	3,787
ng	3	547	763	1,009	799	157	-	-	3,275
Assurance	3	104	287	478	194	12	-	-	1,075
	3	737	4,308	1,018	32	7	-	-	6,103
nt	4								
ngineering	4								
	4								
	4								
	4	45	286	49	-	-	-	-	381
tors	4	173	2,238	341	-	-	-	-	2,752
echanisms	4								
l	4								
	4	233	1,221	295	-	-	-	-	1,743
	4								
stem	4								
ing	4								
	4	286	257	129	32	7	-	-	711
Equip	4	-	306	203	-	-	-	-	510
	3	737	4,308	1,018	32	7	-	-	6,103
	3	564	2,071	677	32	7	-	-	3,350
mbly Test & Check out	3	162	870	1,303	27	-	-	-	2,368
ececraft	2	14,725	28,896	29,709	11,401	1,213	-	-	85,944
vices	2	-	11,465	21,001	14,388	8,243	-	-	55,097
s System (MOS)	2	199	196	593	1,480	2,061	2,315	159	7,003
m (GDS)	2	199	196	593	1,480	1,268	1,150	-	4,886
Assembly, Test & Check	2	86	140	243	2,163	318	-	-	3,550
Outreach	2	636	419	606	779	993	743	232	4,409
	2	541	11,660	12,432	5,813	2,109	1,390	137	34,082
	1								
Corporate Gov	1								
Center Management Operations (CMO)	1								

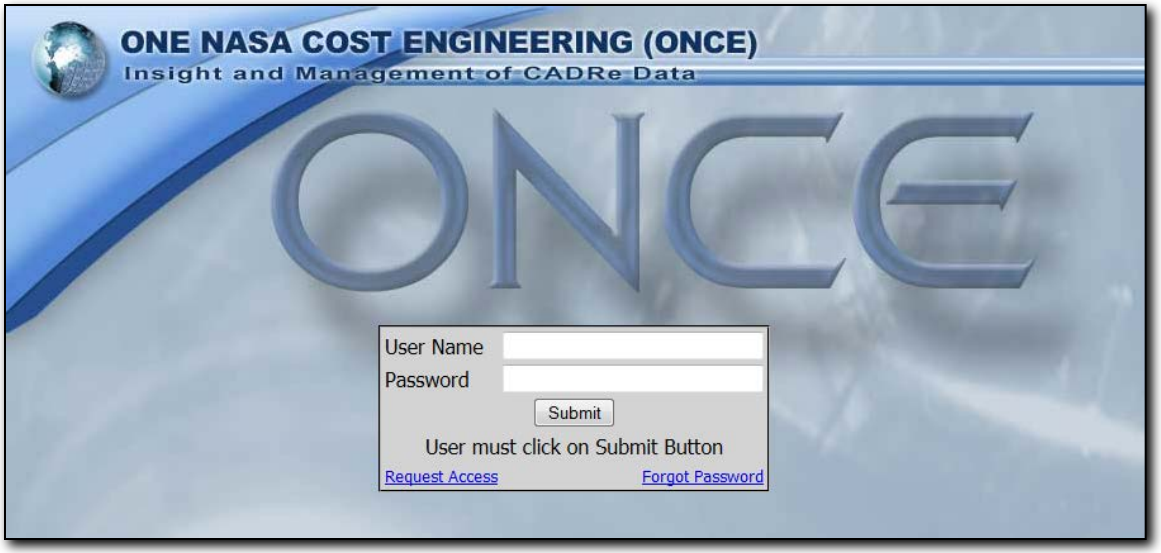
B	C Lev	D Description of inclusions and exclusions
Mission Analysis/System Eng	1	
	2	Includes responsibility for the overall mission implementation. This includes all efforts associated with project level planning and control, directing and centralizing efforts and interactions, as well as
sineering	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
surance Management	2	Includes all efforts associated with the development and implementation of the Project's Mission Assurance program throughout Phase A/B. This includes the identification and control of Project to choice risks, preparing the Mission Assurance Plan and providing oversight of the mission
ation	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 orbits, analysis, post-flight mission data evaluation, oversight of the launch service and
	1	
erScience Management	2	Includes all costs for the PI's time except for time spent on the STScI/Champagne Liaison. It includes the percentage donated to EPO (WBS 01000), to the target characterization observing and analysis (WBS 02000), to data analysis (WBS 2.6000), to archive (WBS 2.6000), to data access
tion	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 Mission Extension (WBS 2.5300)
ed Camera	2	Combined into 22000
n Studies	2	Includes studying the cratering process, both in the laboratory and via numerical simulation.
	2	Includes the efforts of the PI and Deputy PI in carrying out liaison with the STScI/Champagne
	2	This element is not used in Phase A/B/C since the analysis of the data from the target characterization, assessment, is included under that element
tware	2	Includes the modification of software for processing the data at the Overall Science Data Center and the costs of installing available software at the spacecraft at JPL for near-real-time display of
	2	Includes archiving the data into the PDS. In Phase A/B/C it includes mainly the preparation of the Archiving plan, determination of the archived products to be included in the archive, preliminary design of PDS labels and volumes, assembling associated archival documentation, and preliminary
	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 program, reviewing
	1	
	2	Includes the management of the flight system development and program liaison with the support functions of system engineering, product assurance, fabrication, sub-contract and material
	2	Includes the choice of management of the flight system subsystem and mission including design, technical management of the subsystem equipment
	2	
	2	
	2

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

Future
+30 CADRes/Yr
+6 Missions/Yr

Initial Mass Growth Study

Enhanced Mass Growth Study
+ 1 additional Metric

Trending on Mass Growth
+2 additional Metrics

Continuous Trending
Additional Metrics
Normalized Dataset

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

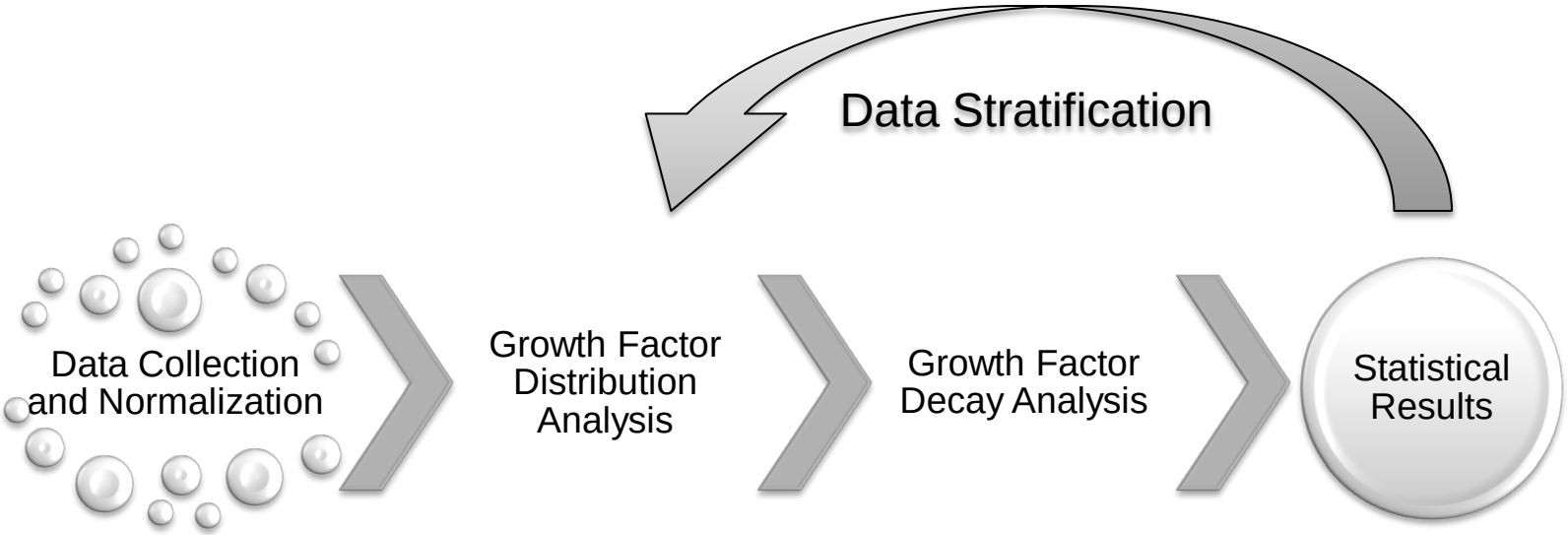
- As the project nears the launch milestone, mass estimates increase in accuracy
  - Mean of the mass values by milestone approaches 1 (zero growth) – Getting better at predicting Launch Mass
  - Standard Deviation decreases as the mass technical baseline matures – Lower variability in mass range
- An Exponential Decay function can be used to model the average decrease in mass growth as the technical baseline matures
- Exponential Decay is a decrease in a value N according to the law $N(x) = N_0 e^{-\lambda x}$ where:
  - λ is the decay constant
  - $N_0 = N(0)$ is the initial value

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

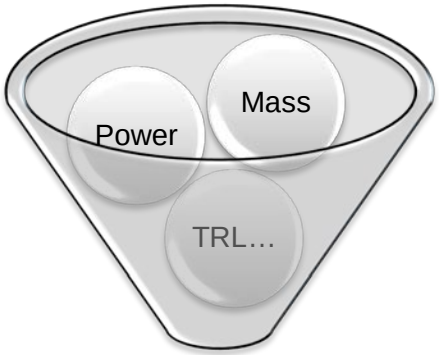
Study Process



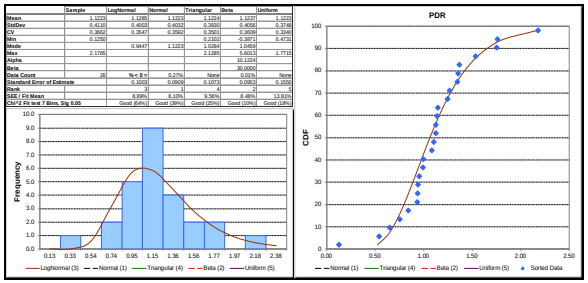
- Assessment and evaluation of source data, extraction, normalization, and format conducted prior to data analysis
- Statistical Analysis software facilitates Growth Factor and Decay analysis – used COTS tools (Excel and CO$TAT from ACEIT Software suite)
- Data Stratifications include selection of Milestone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

Analysis Framework

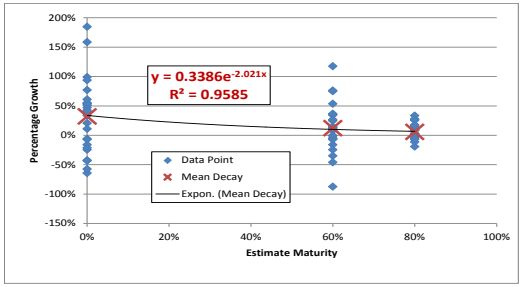
Data Collection

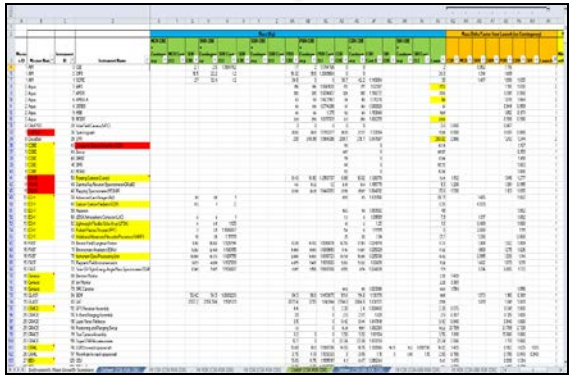


Growth Factor Analysis



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

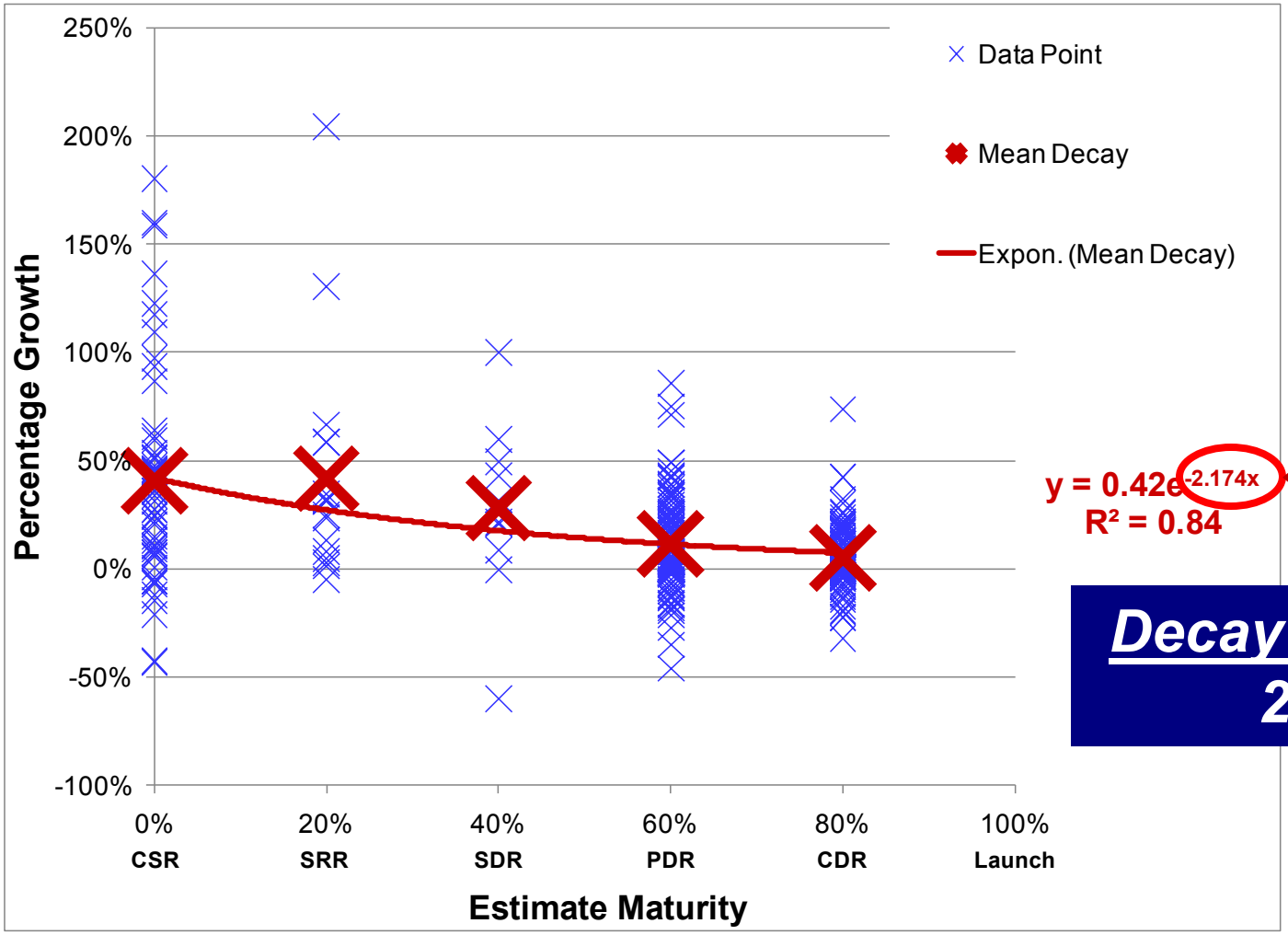
b = Mass Growth Decay Constant

t = Estimate Maturity Parameter

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

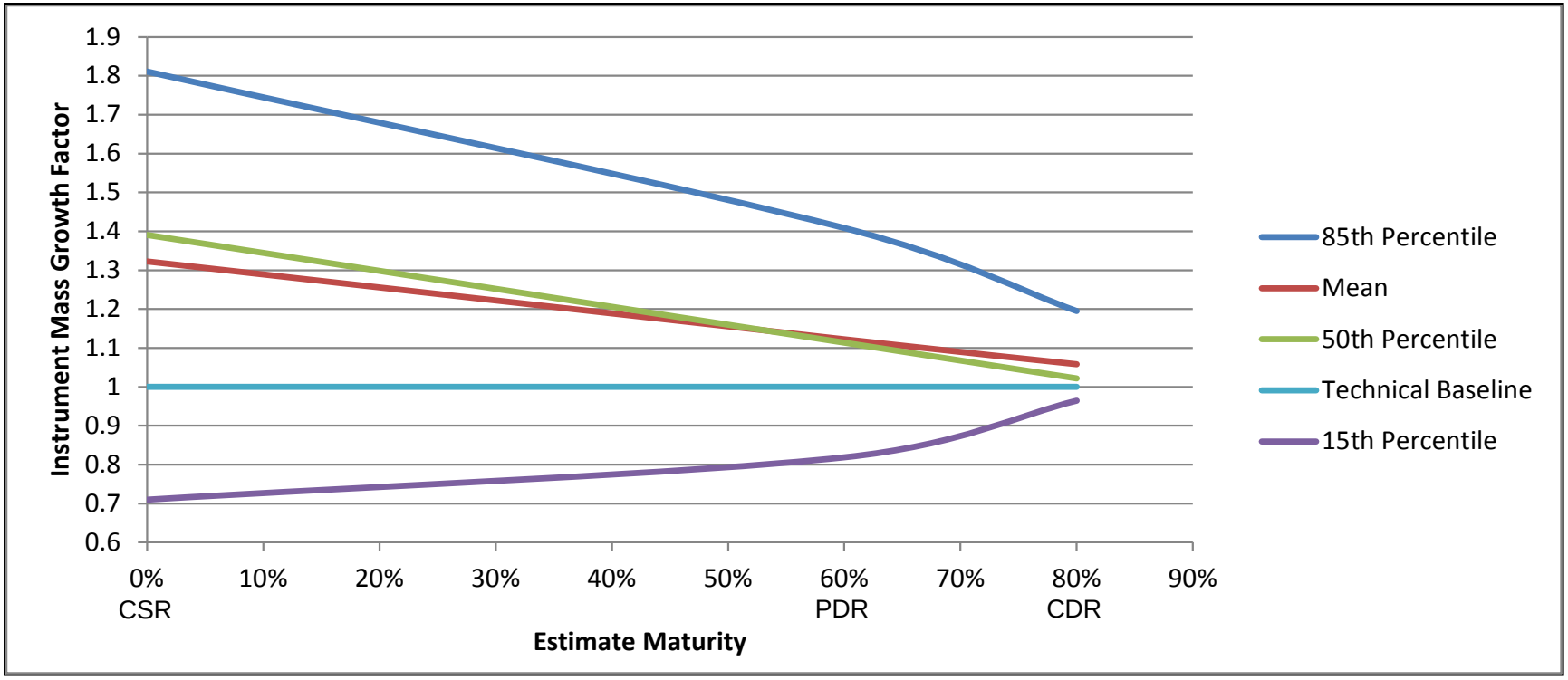
Enables Analysts to Use at any Point in Design Cycle and not just at Milestones

Deriving a Decay Constant from Mass Growth Data



Decay Constant
2.174

Example of Continuous Mass Growth Decay Model

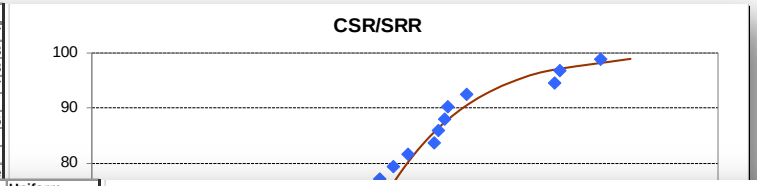


Enhances Analyst Capability to Specify Mass Uncertainty Ranges for CERs and SERs

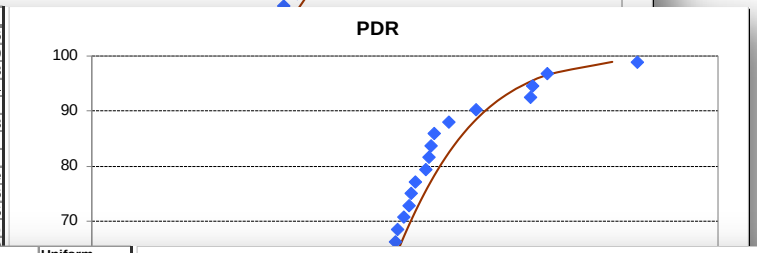
Mass Growth Distributions

Common Milestones – CADRe Data

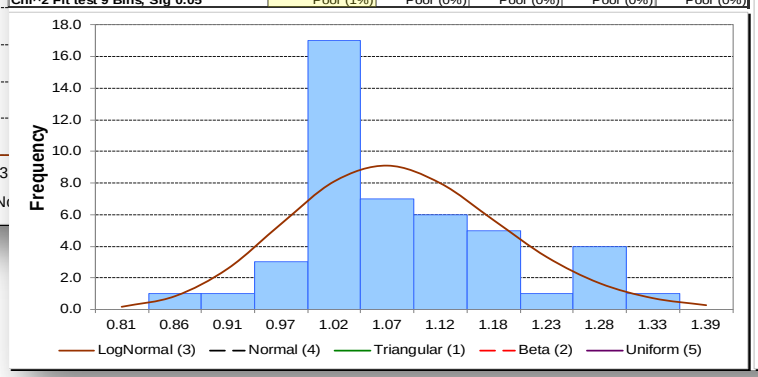
	Sample	LogNormal	Normal	Triangular	Beta	Uniform
Mean	1.3787	1.3853	1.3787	1.3788	1.3800	1.3787
StdDev	0.5359	0.5269	0.5272	0.5210	0.5309	0.5023
CV	0.3887	0.3804	0.3824	0.3779	0.3847	0.3643
Min	0.3571			0.2284	-0.0626	0.5087
Mode	1.5357	1.1312	1.3787	1.1564	1.2101	
Max	2.8462			2.7515	8.5258	2.2486
Alpha					5.9756	
Beta					29.6004	
Data Count	46	% < 0 =	0.45%	None	0.00%	None
Standard Error of Estimate						
Rank						
SEE / Fit Mean						
Chi^2 Fit test 9 Bins, Sig 0.05						

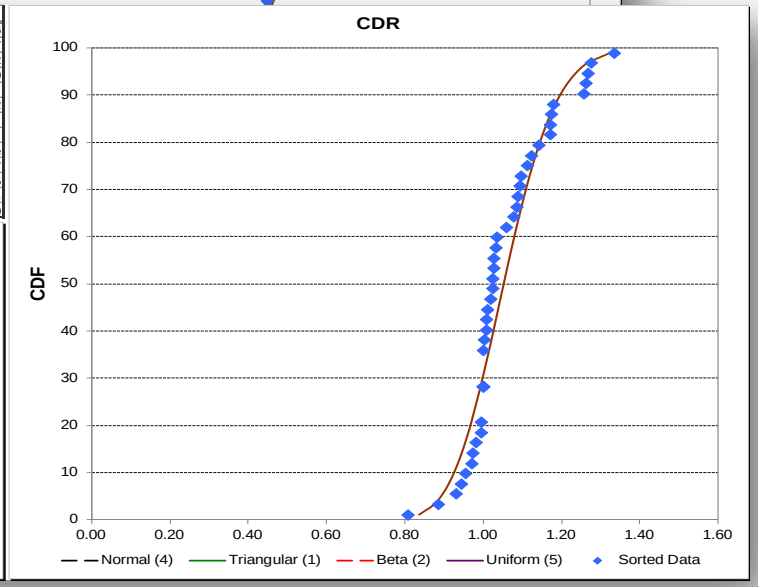


	Sample	LogNormal	Normal	Triangular	Beta	Uniform
Mean	1.1426	1.1447	1.1426	1.1426	1.1430	1.1426
StdDev	0.3350	0.3225	0.3226	0.3144	0.3219	0.2969
CV	0.2932	0.2817	0.2823	0.2751	0.2816	0.2598
Min	0.1250			0.4140	-0.1470	0.6284
Mode		1.0208	1.1426	1.0655	1.0896	
Max	2.1765			1.9483	4.5181	1.6568
Alpha		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



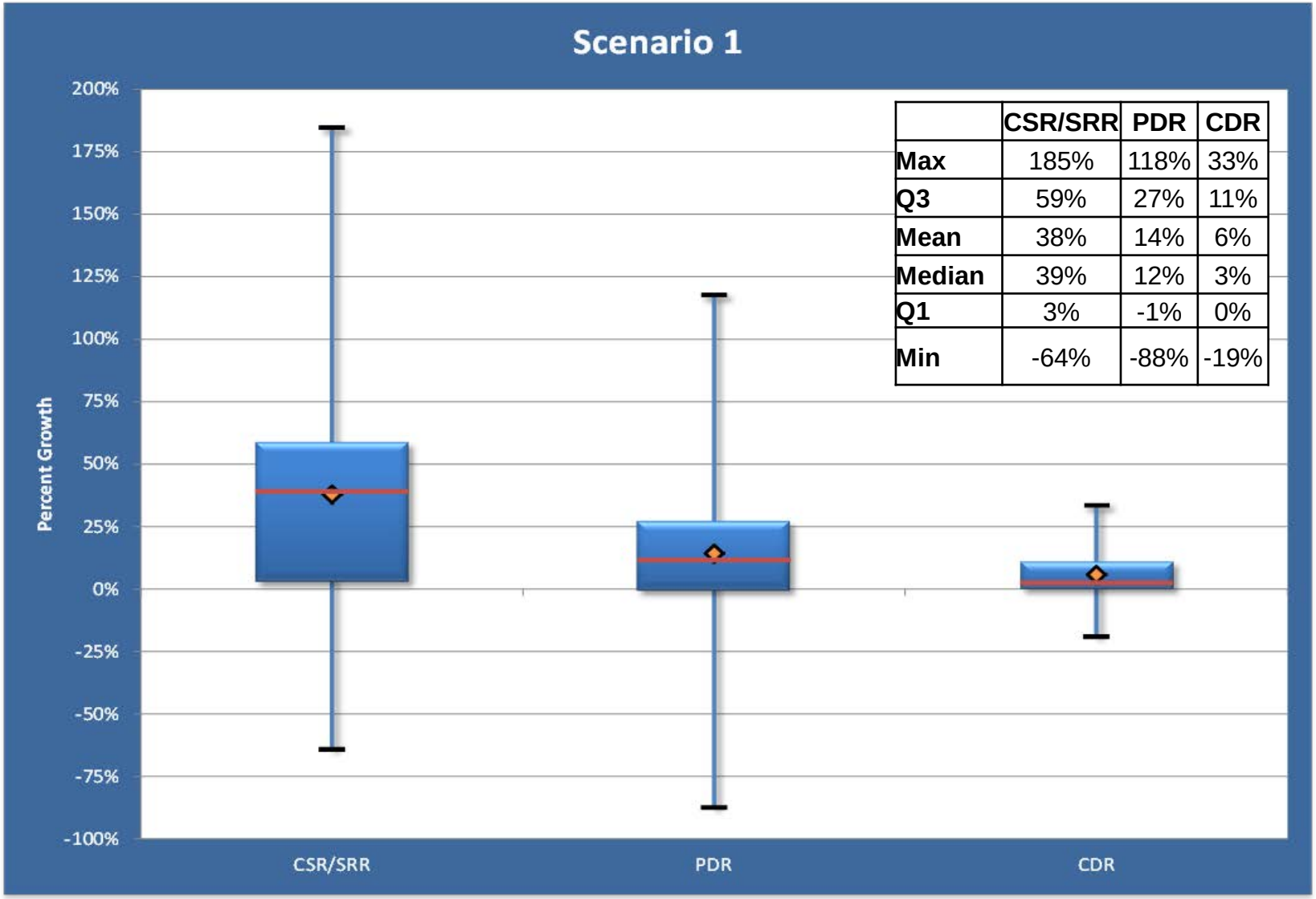
	Sample	LogNormal	Normal	Triangular	Beta	Uniform
Mean	1.0576	1.0576	1.0575	1.0576	1.0578	1.0576
StdDev	0.1080	0.1062	0.1044	0.1043	0.1048	0.0997
CV	0.1021	0.1004	0.0987	0.0986	0.0991	0.0942
Min	0.8085			0.8526	0.9046	0.8850
Mode	1.0000	1.0418	1.0575	0.9764	0.9667	
Max	1.3341			1.3439	1.5016	1.2302
Alpha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

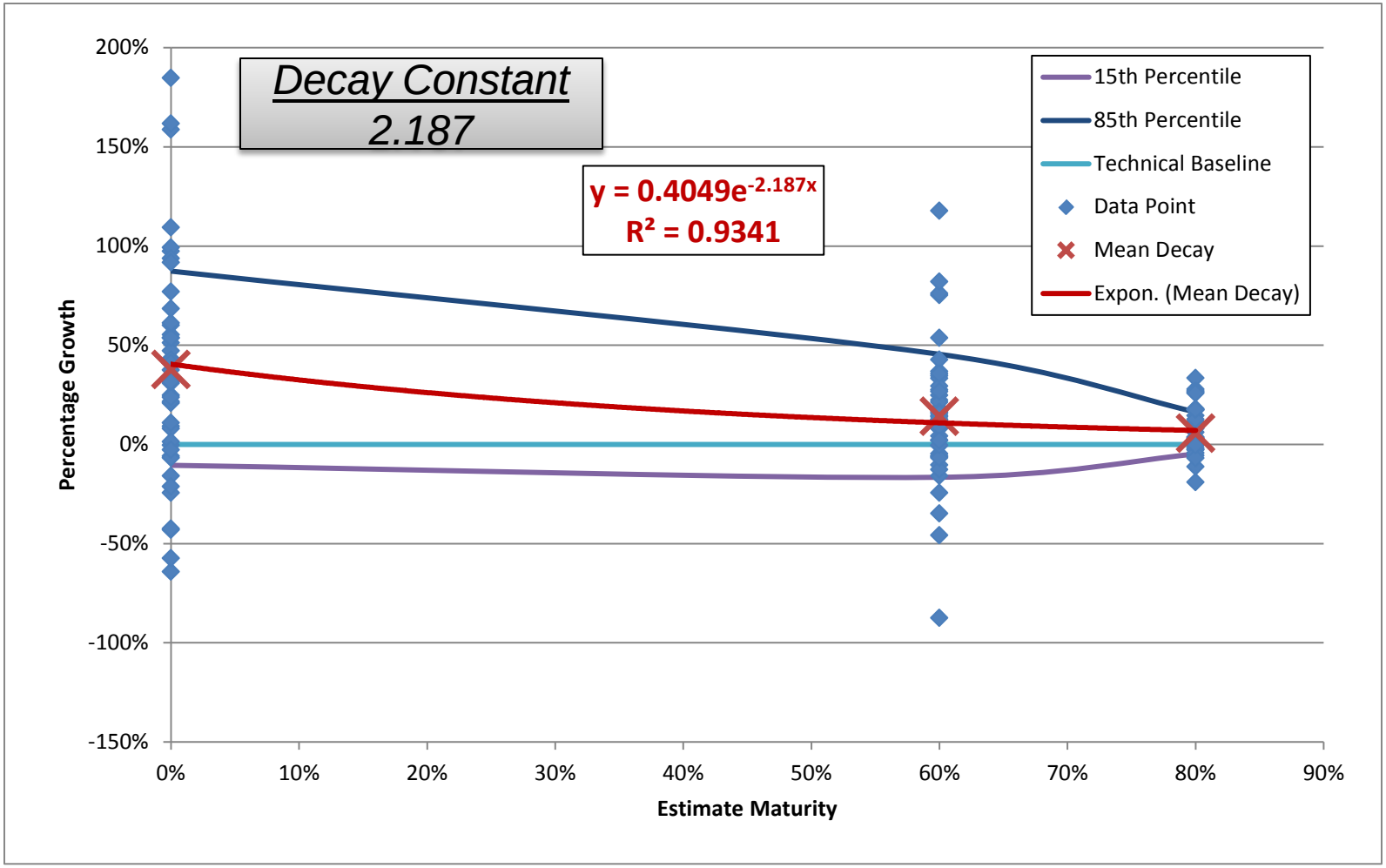
Common Milestones – CADRe Data



	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