



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 discuss the long term strategy of NASA Headquarters in publishing similar results, using a variety of cost driving metrics, on an annual basis. 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



Program Phases		Formulation			Implementation		
Flight Projects Life Cycle Phases	Pre-Phase A: Concept Studies	Phase A: Concept Development SRR/MDR	Phase B: Preliminary Design PDR	Phase C: Detailed Design CDR	Phase D: Fabrication, Assembly & Test SIR Launch	Phase E: Operations & Sustainment	Phase F: Disposal EOM
Traditional Waterfall Development or Directed Missions		1	2	3	4	5	6
AO-Driven Projects	Down Select Step 1	Select Step 2	2	3	4	5	6

Legend

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



Part A Example

Provides Descriptive Info of S/C and Payloads, etc

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 31st, 2005, U.S. time, with approach images available for television. The impact will be visible in small telescopes at distant 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 DUBS/CAT spacecraft and payload.¹¹

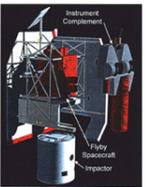


Figure 3 Primary Components of the Deep Impact Flight System (Exploded View)¹²

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 electronic 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), solar range (0.93 to 1.96 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 (7025H 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.

System Overview

Subsystem Description

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:¹⁴

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 spacecraft, impacts the nucleus surface, delivering 28 Gigajoules of kinetic energy to a 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.

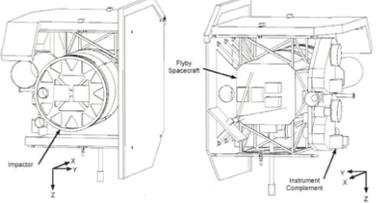


Figure 9 "Impactor First" Flight System Configuration¹⁵

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.¹⁶

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.¹⁷

¹⁴ Technical Approach, *Deep Impact CSR*, 26 March 1999, p. 3-25.
¹⁵ Technical Approach, *Deep Impact CSR*, 26 March 1999, p. 3-9.
¹⁶ Technical Approach, *Deep Impact CSR*, 26 March 1999, p. 3-11.
¹⁷ Technical Approach, *Deep Impact CSR*, 26 March 1999, p. 3-12.
¹⁸ Technical Approach, *Deep Impact CSR*, 26 March 1999, p. 3-22.

Payload Description

Project Management

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. 5000 beam splitter directs the light from the telescope to the two identical CCDs to provide a notionally 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.¹⁰⁰

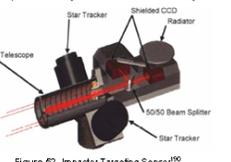


Figure 52: Impactor Targeting Sensor¹⁰⁰

3.4 Common Electronics

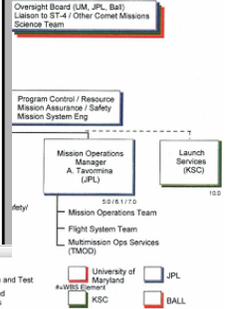
Figure 53, below, is a schematic of the common electronics for the CCD detector supporting the exposed instruments as well as the common architecture for all electronics. The detector electronics include a timing generator, clock drivers, and a set of analog-to-digital processing units. The eight chains for the CCD (two for the HgCdTe FPA) all function synchronously and their outputs are multiplexed to a parallel bus that links directly to the mass memory or are loaded into a first-in first-out (FIFO) buffer for transfer to the SCU. All timing, mechanism control, and data multiplex are coordinated by an Essential Science Node (ESN) micro-controller, which consists of a multi-chip module with a 69000 processor.¹⁰¹

Using 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 download to the DSN. The RS-422 interface is backed up by the MIL-STD 1553 bus, but with 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-3.¹⁰²

The EDMM-3, produced by Spectrum Astro, features 8.2 Gbytes (84 Gbits) of storage space; each unit has two independently accessible, non-volatile disk drives, each capable of 4.1 Gbytes of storage, equivalent to 11,800 full (16-bit) CCD images, and 77,000 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 sequencing will fill the drives to ~90% of their capacity; this data will be available after encounter.¹⁰³

¹⁰⁰ Technical Approach, *Deep Impact CSR*, 26 March 1999, p. 3-35.
¹⁰¹ Technical Approach, *Deep Impact CSR*, 26 March 1999, p. 3-31.
¹⁰² Technical Approach, *Deep Impact CSR*, 26 March 1999, p. 3-35.
¹⁰³ Technical Approach, *Deep Impact CSR*, 26 March 1999, p. 3-35.
¹⁰⁴ Technical Approach, *Deep Impact CSR*, 26 March 1999, p. 3-35.

Figure 54. Organizational Structure for Phase A/B-C/D¹⁰⁴



¹⁰⁴ Management Plan, *Deep Impact CSR*, 26 March 1999, pp. 4-2 to 4-3.
¹⁰⁵ Management Plan, *Deep Impact CSR*, 26 March 1999, p. 4-3.
¹⁰⁶ Management Plan, *Deep Impact CSR*, 26 March 1999, p. 4-3.



Part B Example



Shows the Technical Data (Mass, Power)

Payload	Instrument Name	Instrument #	Builder	Design Life	Number of Channels	Peak Data Rate	Duty Cycle
Instrument 1 (HR)	High Resolution Instrument	1	Contractor				
Instrument 2 (HR)	Medium Resolution Instrument	2	Contractor				
Instrument 3 (ITS)	Impactor Targeting Sensor	3	Contractor				

Payload	Assembly Name	Mass OBE+Cont (kg)	Average Power OBE (W)	Dimensions (cm)	Flight Hazards	Percent New Design	Quantity (Units)	Tech Param 1	Tech Param 2	Tech Param 3	Tech Param 4	Tech Param 5	Tech Param 6	Notes
Instrument 1	Payload Total	100.41 kg	75.75 W											
	Total	100.41 kg	75.75 W											
	Optics	0.29 kg	4.00 W											
	Sensor/Receiver	3.06 kg	0.00 W					Type	Pixel Size					
	Structure/Mechanical	24.75 kg	0.00 W											
	Thermal Control	2.43 kg	0.00 W											
	Electronics	10.07 kg	25.75 W											
	Power								Peak Power	Duty Cycle				
	Planning Subsystem													
	Harness, Cabling, etc.	2.28 kg	0.00 W	TBD										
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0.00 W	TBD											
Optics														
Electronics														
Planning Subsystem														
Harness, Cabling, etc.	2.28 kg	0												



Part C Example



Shows Cost data by WBS

Deep Impact - Report as of 24 March 1999		Summary Costs (Thousands of FY1999 Dollars)							Total
Project WBS Elements		FY2000	FY2001	FY2002	FY2003	FY2004	FY2005	FY2006	
0.0	Project Management / Mission Analysis / System Eng	2,041	1,855	2,204	2,248	659	-	-	9,022
0.0	Science Team	766	530	688	758	338	-	-	3,080
0.0	Flight System	19,174	42,573	37,344	14,786	1,604	-	-	114,481
0.1	Program Management	1,247	1,036	1,482	1,449	468	-	-	5,732
0.2	System Engineering	892	645	315	11	-	-	-	1,863
0.2	Instruments	3,450	13,677	7,635	1,644	255	-	-	26,661
0.2.1	Instrument Management	599	1,970	1,525	528	64	-	-	7,727
0.2.2	Instrument Systems Engineering	547	752	1,009	799	157	-	-	3,272
0.2.3	Instrument Product Assurance	104	237	478	194	12	-	-	1,027
0.2.4	Telecom	125	359	145	-	-	-	-	1,144
0.2.5	Spectral Camera	247	4,476	882	-	-	-	-	6,505
0.2.6	Electronic Module	499	3,444	385	-	-	-	-	5,328
0.2.7	Instrument Software	957	771	303	95	22	-	-	2,148
0.2.8	HRI	50	257	609	-	-	-	-	916
0.2.9	MRII	62	271	526	-	-	-	-	859
0.2.A	Impactor Target Sensor	49	231	752	27	-	-	-	1,059
0.2.B	Ground Support Equipment	-	918	610	-	-	-	-	1,528
0.4	Flyby Spacecraft	9,680	19,920	20,526	7,032	717	-	-	57,875
0.4.1	Program Management	2,179	1,948	2,834	2,322	391	-	-	9,574
0.4.2	System Engineering	830	781	852	458	111	-	-	3,032
0.4.3	Product Assurance	425	542	702	512	-	-	-	2,181
0.4.4	Propulsion	403	1,454	1,096	186	197	-	-	3,336
0.4.5	Telecommunications	723	2,678	1,826	424	5	-	-	5,656
0.4.6	Electrical Power	644	3,192	2,049	304	5	-	-	6,194
0.4.7	Structure	764	2,720	3,411	239	-	-	-	7,134
0.4.8	C&DH	608	3,688	2,527	750	-	-	-	7,563
0.4.9	ADCS	429	977	2,071	489	-	-	-	3,976
0.4.A	Thermal	269	445	766	193	-	-	-	1,673
0.4.C	Software	2,027	704	679	-	-	-	-	3,420
0.4.D	Integration & Test	75	212	1,035	897	-	-	-	2,919
0.4.E	Ground Support Equipment	285	678	677	256	-	-	-	1,896
0.5	Impactor	2,905	7,245	7,385	2,909	29	-	-	20,477
0.6	Deep Impact Integration & Test	-	-	1,741	136	-	-	-	1,877
0.6.1	System Integration & Test Management	-	-	284	21	-	-	-	305
0.6.2	Flyby S/C and Impactor Integration & Test	-	-	1,035	114	-	-	-	1,149
0.6.3	System MGSE	-	-	172	-	-	-	-	172
0.6.4	System EGSE	-	-	250	-	-	-	-	250
0.0	Launch Site & Orbital Operations	86	140	242	422	783	-	-	1,673
0.1	Pre-Launch Planning	86	140	242	237	67	-	-	772
0.2	Launch Site Support	-	-	-	165	606	-	-	771
0.4	Flight Operations	-	-	-	109	-	-	-	109
0.0	Pre-Launch GDS/MOS Development	398	291	1,187	2,959	978	-	-	5,913
0.0	Mission Operations and Data Analysis	-	-	-	3,471	5,424	1,265	-	10,170
0.1	Mission Operations	-	-	-	1,572	2,315	159	-	4,046
0.1.3	Phase E Mission Operations	-	-	-	1,572	2,315	159	-	4,046
0.2	Science Team	-	-	-	1,599	5,111	1,105	-	6,815
0.0	Deep Space Network (DSN) or Other Tracking Service	-	-	-	-	-	-	-	-
0.0	Education and Public Outreach	636	419	606	779	993	743	232	4,409
0.0	Launch Services	-	-	-	162	870	1,909	27	2,968
Subtotal		22,001	45,909	42,272	21,972	8,826	6,149	1,497	140,744
Total JPL Reserves		541	11,660	12,432	5,813	2,109	1,390	137	34,082
Total		22,442	57,569	54,704	27,785	10,935	7,559	1,634	182,826
ELV and Launch Services		-	11,465	21,001	14,388	8,243	-	-	55,097
DSN and Tracking Support		-	-	-	779	1,150	-	-	1,929
TOTAL NASA COST		22,442	69,034	75,705	42,173	19,957	6,709	1,634	239,854
Ball Aerospace Contribution		500	500	1,325	825	-	-	-	3,150
Flight System		500	-	-	-	-	-	-	3,150
Instruments		2,500	-	-	-	-	-	-	500
Software		500	-	-	-	-	-	-	500
Impactor		-	500	975	525	-	-	-	2,000
Ground Support Equipment		-	500	975	525	-	-	-	2,000
Deep Impact Integration & Test		-	-	360	306	-	-	-	666

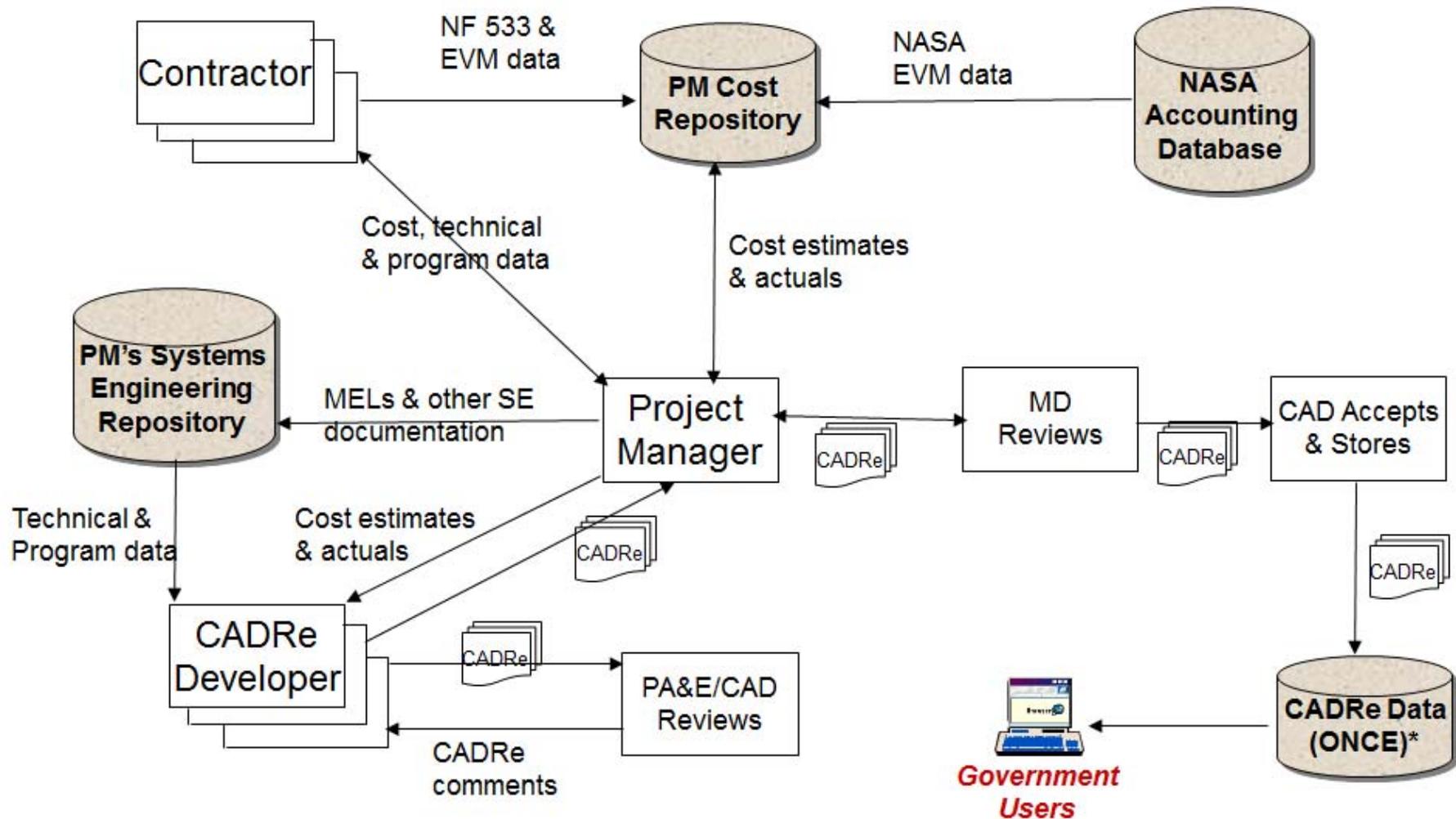
Summary Costs (Thousands of FY1999 Dollars)

WBS Elements	Level	FY2000	FY2001	FY2002	FY2003	FY2004	FY2005	FY2006	Total
0.0	1	22,642	69,034	75,705	42,173	19,957	6,709	1,634	239,854
0.1	2	680	618	735	756	220	-	-	3,009
0.2	2	680	618	735	756	220	-	-	3,009
0.4	2	766	530	688	758	2,237	3,111	1,105	3,195
0.5	3	539	1,010	1,525	528	64	-	-	3,787
0.6	4	45	286	49	-	-	-	-	381
0.7	4	173	2,238	341	-	-	-	-	2,752
0.8	4	293	1,221	295	-	-	-	-	1,743
0.9	4	286	257	123	32	7	-	-	711
0.0	3	737	4,308	1,018	32	7	-	-	6,103
0.1	3	564	2,071	677	32	7	-	-	3,350
0.2	3	162	870	1,909	27	-	-	-	2,968
0.0	2	14,725	28,836	29,709	11,401	1,213	-	-	85,944
0.1	2	-	11,465	21,001	14,388	8,243	-	-	55,097
0.2	2	193	196	533	1,480	2,061	2,315	153	7,003
0.3	2	193	196	533	1,480	1,268	1,150	-	4,886
0.4	2	86	140	243	2,163	318	-	-	3,550
0.5	2	636	419	606	779	393	743	232	4,409
0.6	2	541	11,660	12,432	5,813	2,109	1,390	137	34,082

WBS Element	Level	Description of inclusions and exclusions
0.0	1	Include all costs for the FY1999 except for the space to the STAGS mission. Includes the percentage budget for EPO (WBS 1999) to the target characterization, observing and science (WBS 2000) and the target characterization, observing and science (WBS 2001) and the target characterization, observing and science (WBS 2002) and the target characterization, observing and science (WBS 2003) and the target characterization, observing and science (WBS 2004) and the target characterization, observing and science (WBS 2005) and the target characterization, observing and science (WBS 2006) and the target characterization, observing and science (WBS 2007) and the target characterization, observing and science (WBS 2008) and the target characterization, observing and science (WBS 2009) and the target characterization, observing and science (WBS 2010) and the target characterization, observing and science (WBS 2011) and the target characterization, observing and science (WBS 2012) and the target characterization, observing and science (WBS 2013) and the target characterization, observing and science (WBS 2014) and the target characterization, observing and science (WBS 2015) and the target characterization, observing and science (WBS 2016) and the target characterization, observing and science (WBS 2017) and the target characterization, observing and science (WBS 2018) and the target characterization, observing and science (WBS 2019) and the target characterization, observing and science (WBS 2020) and the target characterization, observing and science (WBS 2021) and the target characterization, observing and science (WBS 2022) and the target characterization, observing and science (WBS 2023) and the target characterization, observing and science (WBS 2024) and the target characterization, observing and science (WBS 2025) and the target characterization, observing and science (WBS 2026) and the target characterization, observing and science (WBS 2027) and the target characterization, observing and science (WBS 2028) and the target characterization, observing and science (WBS 2029) and the target characterization, observing and science (WBS 2030) and the target characterization, observing and science (WBS 2031) and the target characterization, observing and science (WBS 2032) and the target characterization, observing and science (WBS 2033) and the target characterization, observing and science (WBS 2034) and the target characterization, observing and science (WBS 2035) and the target characterization, observing and science (WBS 2036) and the target characterization, observing and science (WBS 2037) and the target characterization, observing and science (WBS 2038) and the target characterization, observing and science (WBS 2039) and the target characterization, observing and science (WBS 2040) and the target characterization, observing and science (WBS 2041) and the target characterization, observing and science (WBS 2042) and the target characterization, observing and science (WBS 2043) and the target characterization, observing and science (WBS 2044) and the target characterization, observing and science (WBS 2045) and the target characterization, observing and science (WBS 2046) and the target characterization, observing and science (WBS 2047) and the target characterization, observing and science (WBS 2048) and the target characterization, observing and science (WBS 2049) and the target characterization, observing and science (WBS 2050) and the target characterization, observing and science (WBS 2051) and the target characterization, observing and science (WBS 2052) and the target characterization, observing and science (WBS 2053) and the target characterization, observing and science (WBS 2054) and the target characterization, observing and science (WBS 2055) and the target characterization, observing and science (WBS 2056) and the target characterization, observing and science (WBS 2057) and the target characterization, observing and science (WBS 2058) and the target characterization, observing and science (WBS 2059) and the target characterization, observing and science (WBS 2060) and the target characterization, observing and science (WBS 2061) and the target characterization, observing and science (WBS 2062) and the target characterization, observing and science (WBS 2063) and the target characterization, observing and science (WBS 2064) and the target characterization, observing and science (WBS 2065) and the target characterization, observing and science (WBS 2066) and the target characterization, observing and science (WBS 2067) and the target characterization, observing and science (WBS 2068) and the target characterization, observing and science (WBS 2069) and the target characterization, observing and science (WBS 2070) and the target characterization, observing and science (WBS 2071) and the target characterization, observing and science (WBS 2072) and the target characterization, observing and science (WBS 2073) and the target characterization, observing and science (WBS 2074) and the target characterization, observing and science (WBS 2075) and the target characterization, observing and science (WBS 2076) and the target characterization, observing and science (WBS 2077) and the target characterization, observing and science (WBS 2078) and the target characterization, observing and science (WBS 2079) and the target characterization, observing and science (WBS 2080) and the target characterization, observing and science (WBS 2081) and the target characterization, observing and science (WBS 2082) and the target characterization, observing and science (WBS 2083) and the target characterization, observing and science (WBS 2084) and the target characterization, observing and science (WBS 2085) and the target characterization, observing and science (WBS 2086) and the target characterization, observing and science (WBS 2087) and the target characterization, observing and science (WBS 2088) and the target characterization, observing and science (WBS 2089) and the target characterization, observing and science (WBS 2090) and the target characterization, observing and science (WBS 2091) and the target characterization, observing and science (WBS 2092) and the target characterization, observing and science (WBS 2093) and the target characterization, observing and science (WBS 2094) and the target characterization, observing and science (WBS 2095) and the target characterization, observing and science (WBS 2096) and the target characterization, observing and science (WBS 2097) and the target characterization, observing and science (WBS 2098) and the target characterization, observing and science (WBS 2099) and the target characterization, observing and science (WBS 2100) and the target characterization, observing and science (WBS 2101) and the target characterization, observing and science (WBS 2102) and the target characterization, observing and science (WBS 2103) and the target characterization, observing and science (WBS 2104) and the target characterization, observing and science (WBS 2105) and the target characterization, observing and science (WBS 2106) and the target characterization, observing and science (WBS 2107) and the target characterization, observing and science (WBS 2108) and the target characterization, observing and science (WBS 2109) and the target characterization, observing and science (WBS 2110) and the target characterization, observing and science (WBS 2111) and the target characterization, observing and science (WBS 2112) and the target characterization, observing and science (WBS 2113) and the target characterization, observing and science (WBS 2114) and the target characterization, observing and science (WBS 2115) and the target characterization, observing and science (WBS 2116) and the target characterization, observing and science (WBS 2117) and the target characterization, observing and science (WBS 2118) and the target characterization, observing and science (WBS 2119) and the target characterization, observing and science (WBS 2120) and the target characterization, observing and science (WBS 2121) and the target characterization, observing and science (WBS 2122) and the target characterization, observing and science (WBS 2123) and the target characterization, observing and science (WBS 2124) and the target characterization, observing and science (WBS 2125) and the target characterization, observing and science (WBS 2126) and the target characterization, observing and science (WBS 2127) and the target characterization, observing and science (WBS 2128) and the target characterization, observing and science (WBS 2129) and the target characterization, observing and science (WBS 2130) and the target characterization, observing and science (WBS 2131) and the target characterization, observing and science (WBS 2132) and the target characterization, observing and science (WBS 2133) and the target characterization, observing and science (WBS 2134) and the target characterization, observing and science (WBS 2135) and the target characterization, observing and science (WBS 2136) and the target characterization, observing and science (WBS 2137) and the target characterization, observing and science (WBS 2138) and the target characterization, observing and science (WBS 2139) and the target characterization, observing and science (WBS 2140) and the target characterization, observing and science (WBS 2141) and the target characterization, observing and science (WBS 2142) and the target characterization, observing and science (WBS 2143) and the target characterization, observing and science (WBS 2144) and the target characterization, observing and science (WBS 2145) and the target characterization, observing and science (WBS 2146) and the target characterization, observing and science (WBS 2147) and the target characterization, observing and science (WBS 2148) and the target characterization, observing and science (WBS 2149) and the target characterization, observing and science (WBS 2150) and the target characterization, observing and science (WBS 2151) and the target characterization, observing and science (WBS 2152) and the target characterization, observing and science (WBS 2153) and the target characterization, observing and science (WBS 2154) and the target characterization, observing and science (WBS 2155) and the target characterization, observing and science (WBS 2156) and the target characterization, observing and science (WBS 2157) and the target characterization, observing and science (WBS 2158) and the target characterization, observing and science (WBS 2159) and the target characterization, observing and science (WBS 2160) and the target characterization, observing and science (WBS 2161) and the target characterization, observing and science (WBS 2162) and the target characterization, observing and science (WBS 2163) and the target characterization, observing and science (WBS 2164) and the target characterization, observing and science (WBS 2165) and the target characterization, observing and science (WBS 2166) and the target characterization, observing and science (WBS 2167) and the target characterization, observing and science (WBS 2168) and the target characterization, observing and science (WBS 2169) and the target characterization, observing and science (WBS 2170) and the target characterization, observing and science (WBS 2171) and the target characterization, observing and science (WBS 2172) and the target characterization, observing and science (WBS 2173) and the target characterization, observing and science (WBS 2174) and the target characterization, observing and science (WBS 2175) and the target characterization, observing and science (WBS 2176) and the target characterization, observing and science (WBS 2177) and the target characterization, observing and science (WBS 2178) and the target characterization, observing and science (WBS 2179) and the target characterization, observing and science (WBS 2180) and the target characterization, observing and science (WBS 2181) and the target characterization, observing and science (WBS 2182) and the target characterization, observing and science (WBS 2183) and the target characterization, observing and science (WBS 2184) and the target characterization, observing and science (WBS 2185) and the target characterization, observing and science (WBS 2186) and the target characterization, observing and science (WBS 2187) and the target characterization, observing and science (WBS 2188) and the target characterization, observing and science (WBS 2189) and the target characterization, observing and science (WBS 2190) and the target characterization, observing and science (WBS 2191) and the target characterization, observing and science (WBS 2192) and the target characterization, observing and science (WBS 2193) and the target characterization, observing and science (WBS 2194) and the target characterization, observing and science (WBS 2195) and the target characterization, observing and science (WBS 2196) and the target characterization, observing and science (WBS 2197) and the target characterization, observing and science (WBS 2198) and the target characterization, observing and science (WBS 2199) and the target characterization, observing and science (WBS 2200) and the target characterization, observing and science (WBS 2201) and the target characterization, observing and science (WBS 2202) and the target characterization, observing and science (WBS 2203) and the target characterization, observing and science (WBS 2204) and the target characterization, observing and science (WBS 2205) and the target characterization, observing and science (WBS 2206) and the target characterization, observing and science (WBS 2207) and the target characterization, observing and science (WBS 2208) and the target characterization, observing and science (WBS 2209) and the target characterization, observing and science (WBS 2210) and the target characterization, observing and science (WBS 2211) and the target characterization, observing and science (WBS 2212) and the target characterization, observing and science (WBS 2213) and the target characterization, observing and science (WBS 2214) and the target characterization, observing and science (WBS 2215) and the target characterization, observing and science (WBS 2216) and the target characterization, observing and science (WBS 2217) and the target characterization, observing and science (WBS 2218) and the target characterization, observing and science (WBS 2219) and the target characterization, observing and science (WBS 2220) and the target characterization, observing and science (WBS 2221) and the target characterization, observing and science (WBS 2222) and the target characterization, observing and science (WBS 2223) and the target characterization, observing and science (WBS 2224) and the target characterization, observing and science (WBS 2225) and the target characterization, observing and science (WBS 2226) and the target characterization, observing and science (WBS 2227) and the target characterization, observing and science (WBS 2228) and the target characterization, observing and science (WBS 2229) and the target characterization, observing and science (WBS 2230) and the target characterization, observing and science (WBS 2231) and the target characterization, observing and science (WBS 2232) and the target characterization, observing and science (WBS 2233) and the target characterization, observing and science (WBS 2234) and the target characterization, observing and science (WBS 2235) and the target characterization, observing and science (WBS 2236) and the target characterization, observing and science (WBS 2237) and the target characterization, observing and science (WBS 2238) and the target characterization, observing and science (WBS 2239) and the target characterization, observing and science (WBS 2240) and the target characterization, observing and science (WBS 2241) and the target characterization, observing



CADRe Process



* One NASA Cost Engineering Database (ONCE)



Completed CADRe's are Stored in ONCE



ONE NASA COST ENGINEERING (ONCE)
Insight and Management of CADRe Data

ONCE

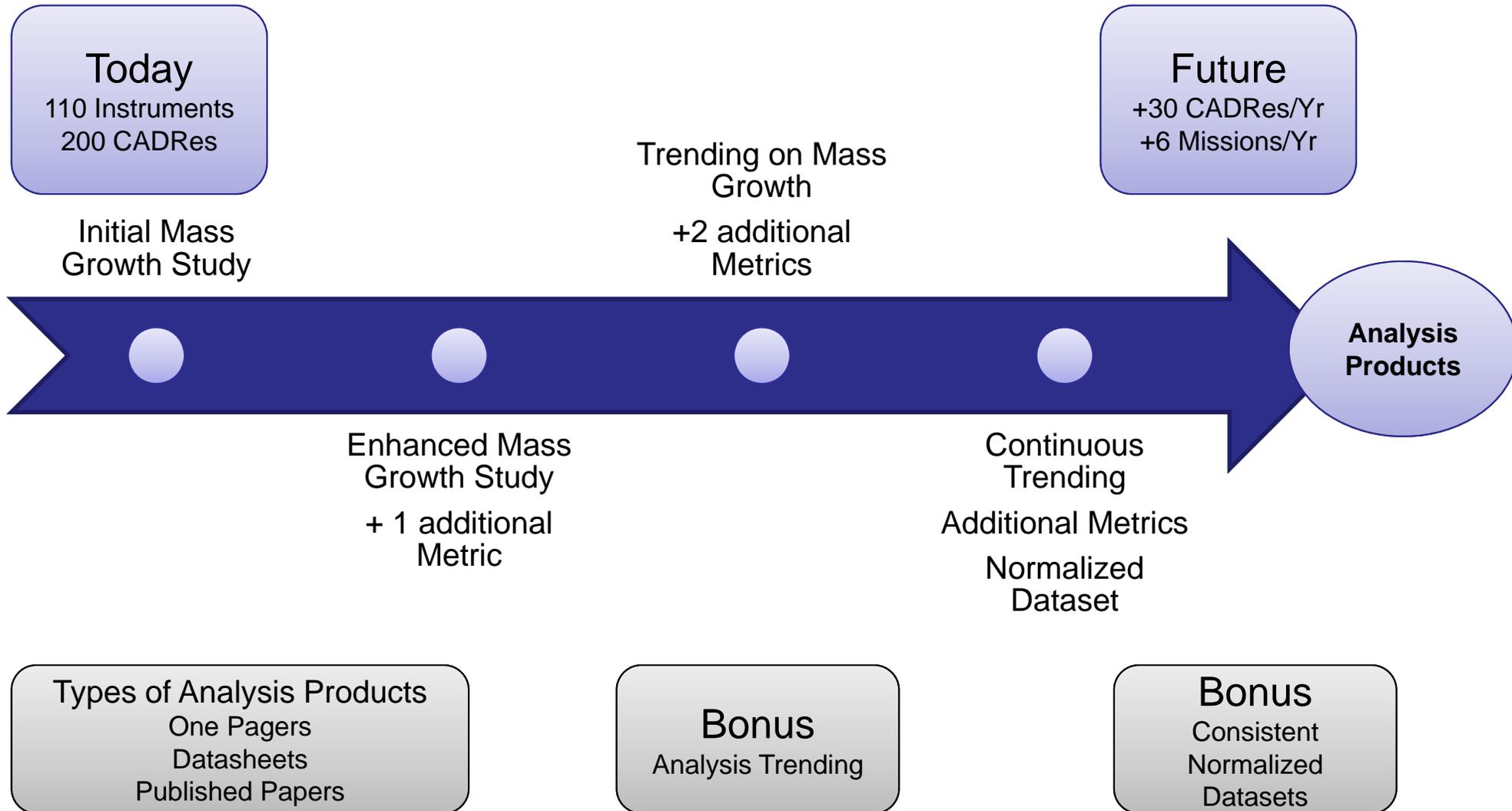
User Name
Password

User must click on Submit Button
[Request Access](#) [Forgot Password](#)

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



CADRe/ONCE Analysis Product Evolution



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

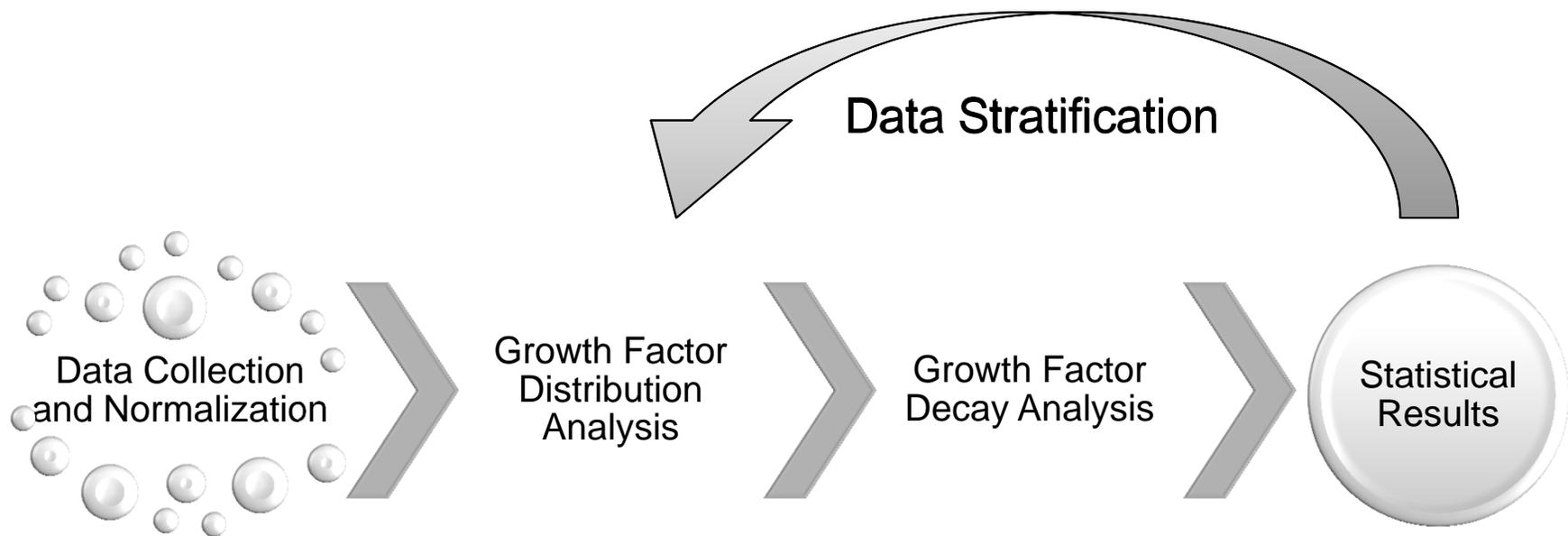


Why Use Mass?



- **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



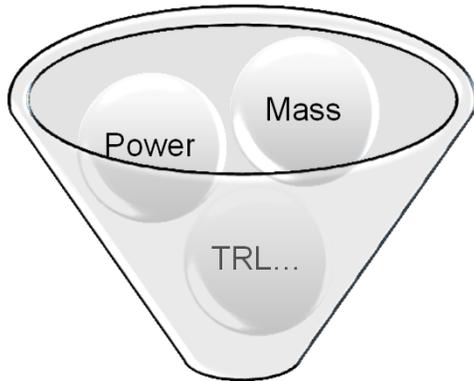
- Assessment and evaluation of source data, extraction, normalization, and format conducted prior to data analysis
- Statistical Analysis software facilitates Growth Factor and Decay analysis – used COTS tools (Excel and CO\$TAT from ACEIT Software suite)
- Data Stratifications include selection of Milestone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



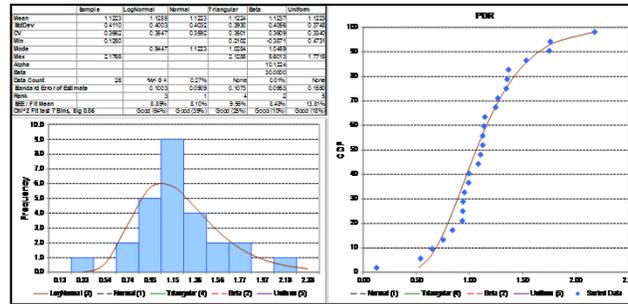
Analysis Framework



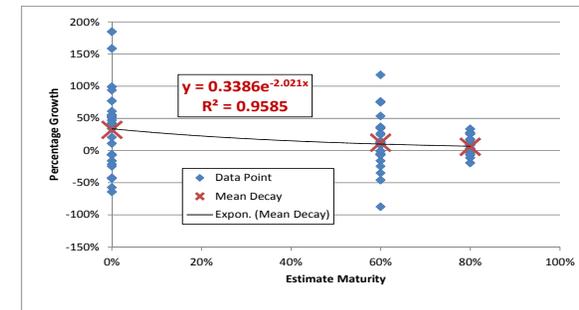
Data Collection



Growth Factor Analysis



Decay Analysis



	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

Consolidated Datasheet

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 = $a * \text{EXP}(b * \text{Mean Percentage Growth})$
 - Calculate decay constant = b



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



Basic Model

Instrument Mass Growth

$$\mathbf{M}_{Adj} \equiv M \left(e^{-bt} \left(\mathbf{K}_{GF} - 1 \right) + 1 \right)$$

M_{Adj} = Growth-adjusted Mass Estimate Distribution

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

M = Technical Baseline Point Estimate of Mass

b = Mass Growth Decay Constant

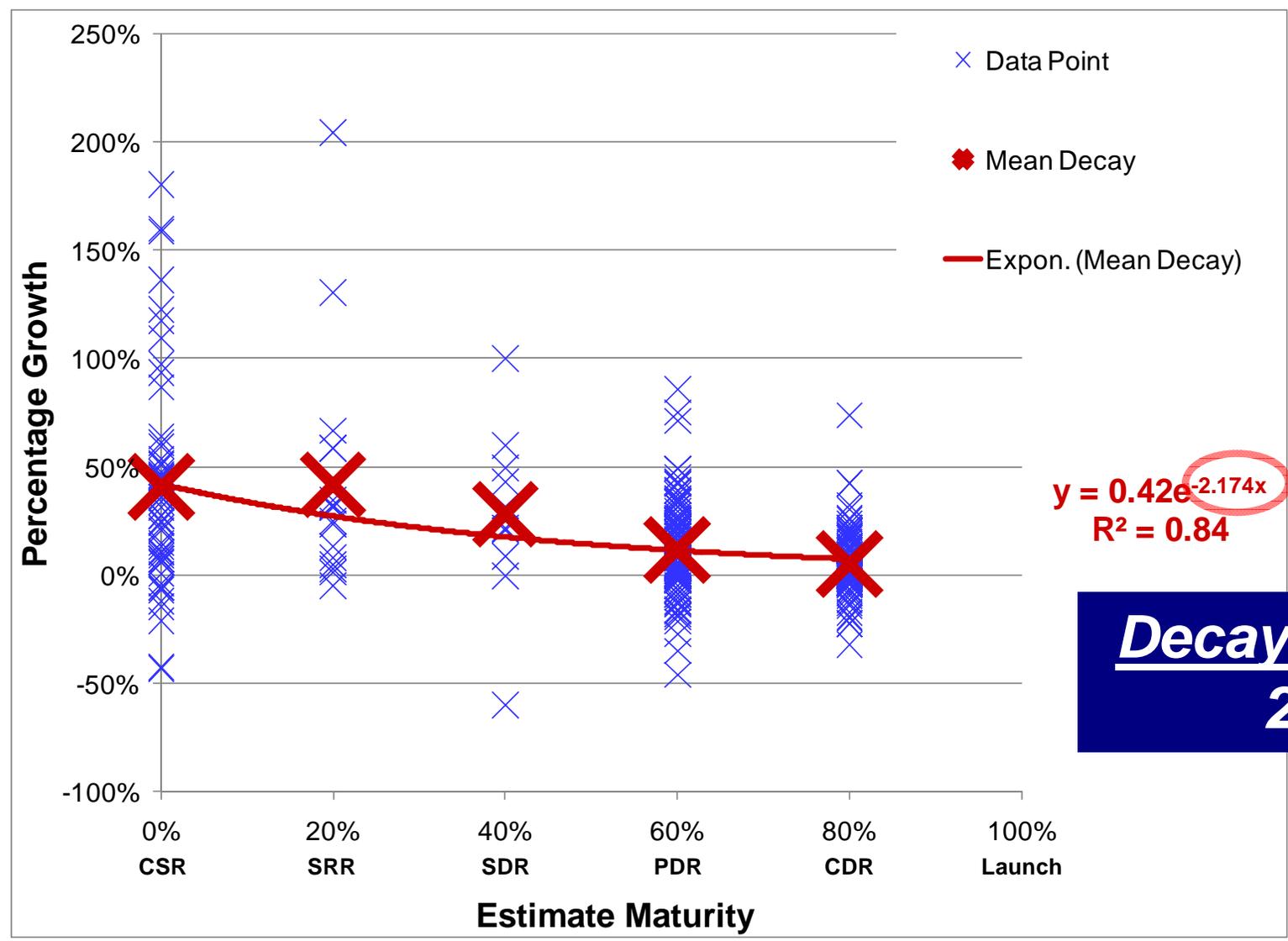
t = Estimate Maturity Parameter

(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

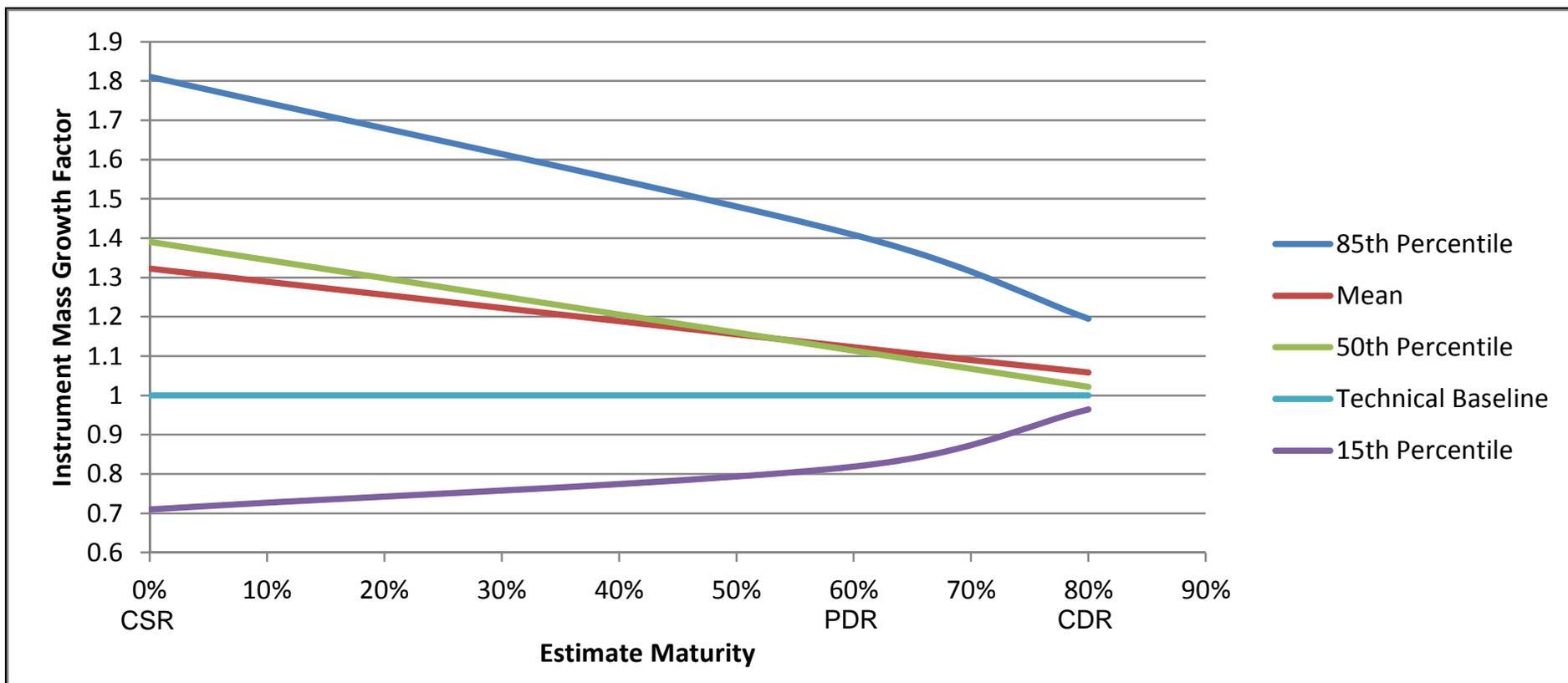


$y = 0.42e^{-2.174x}$
 $R^2 = 0.84$

Decay Constant
2.174



Example of Continuous Mass Growth Decay Model



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

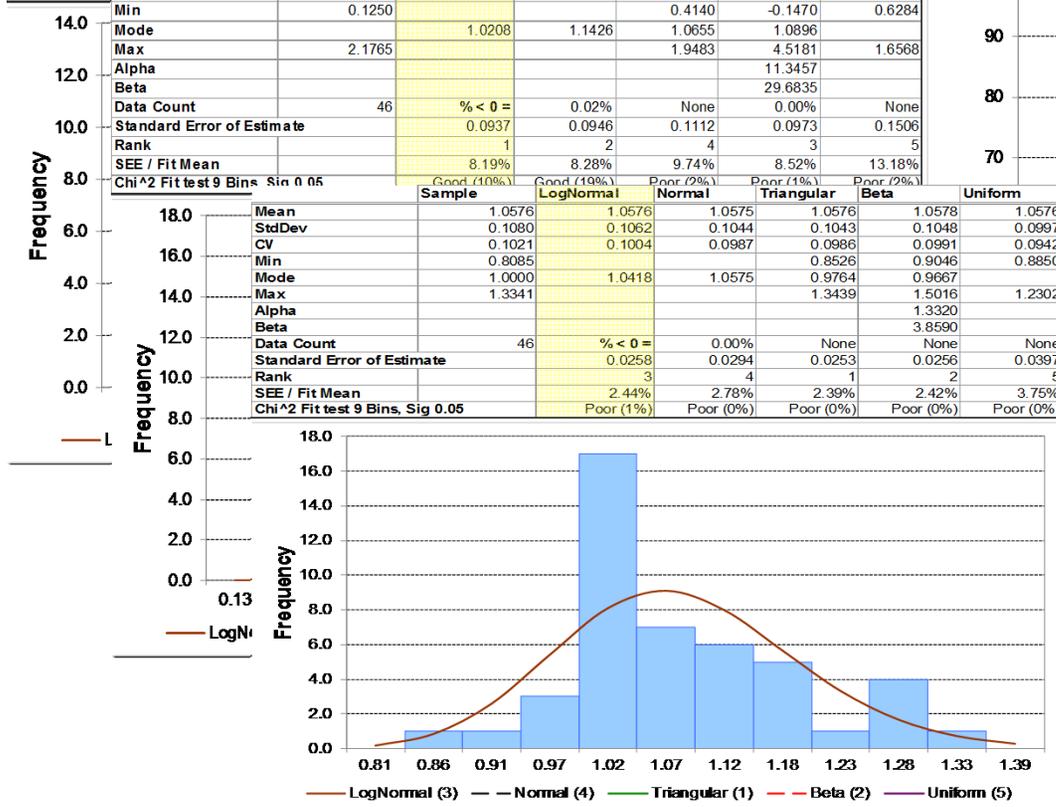
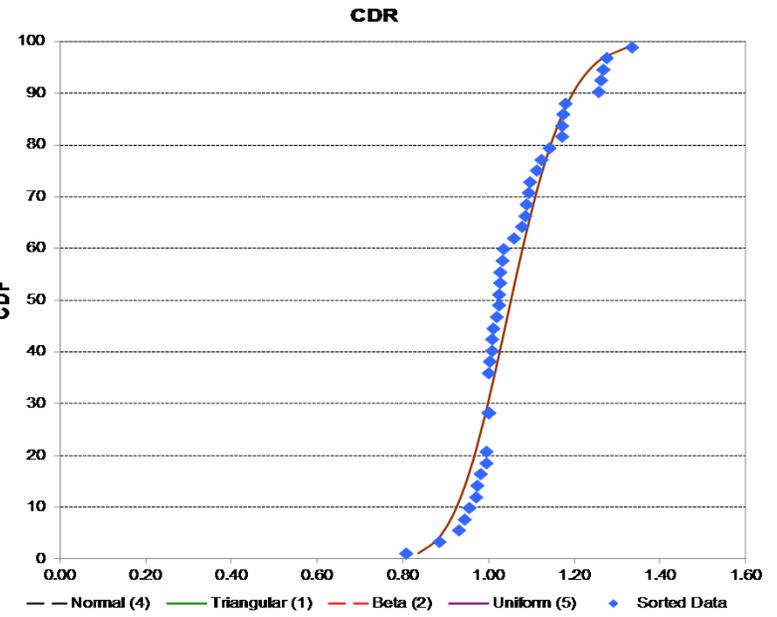
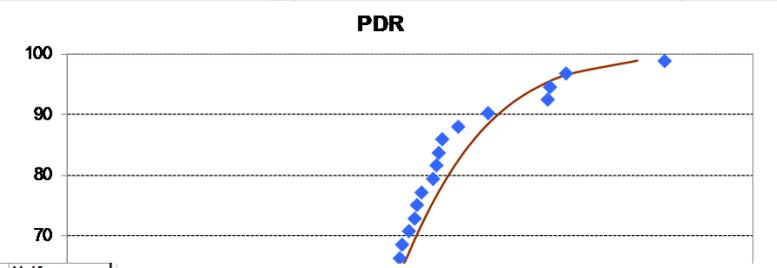
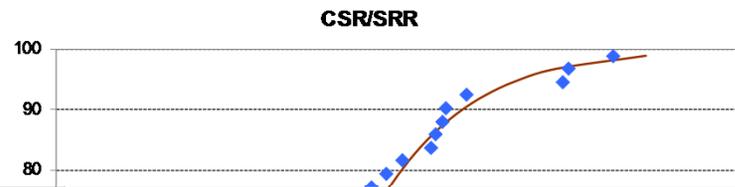


Mass Growth Distributions

Common Milestones – CADRe Data



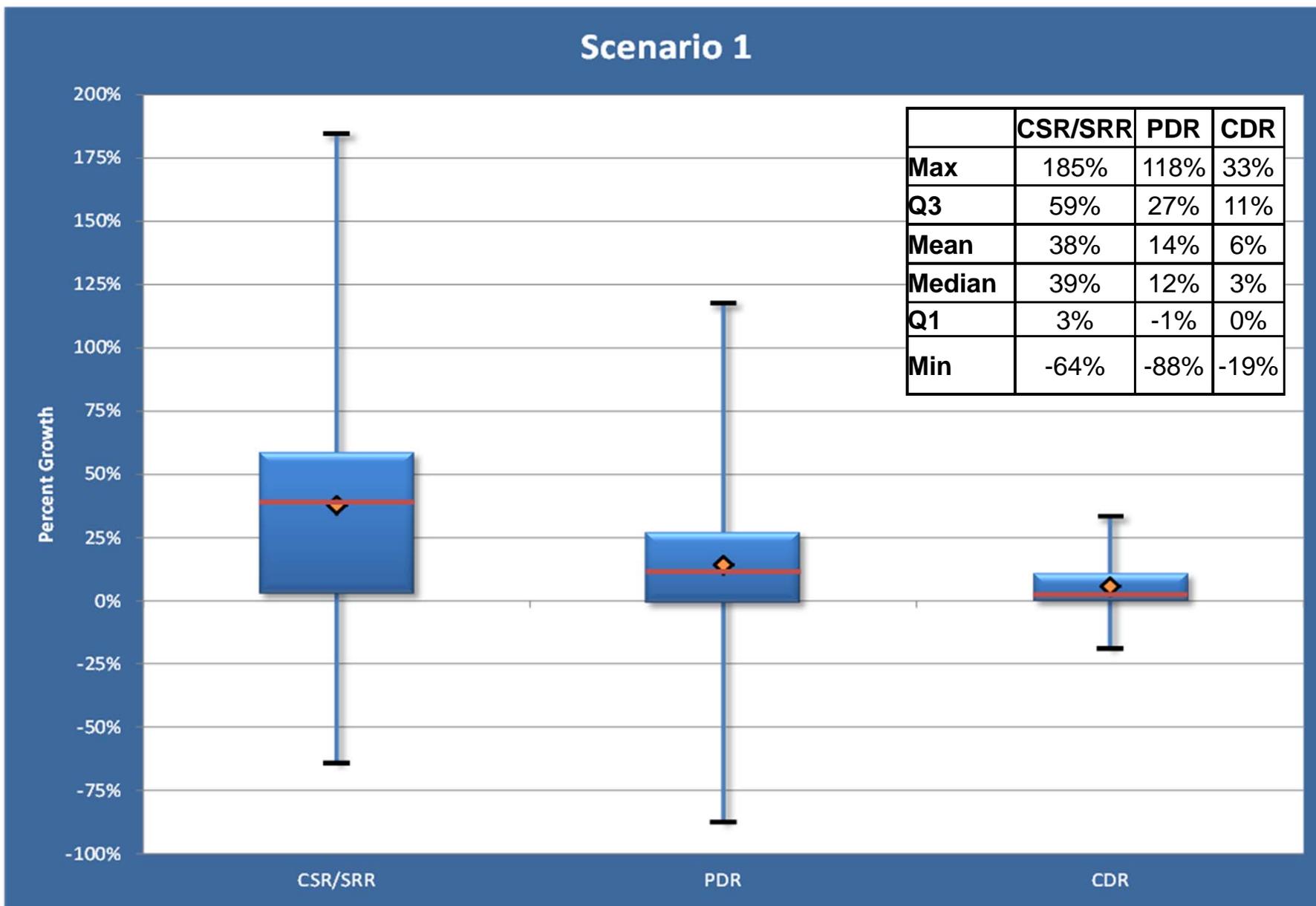
	Sample	LogNormal	Normal	Triangular	Beta	Uniform		
Mean	1.3787	1.3853	1.3787	1.3788	1.3800	1.3787		
StdDev	0.5359	0.5269	0.5272	0.5210	0.5309	0.5023		
CV	0.3887	0.3804	0.3824	0.3779	0.3847	0.3643		
Min	0.3571			0.2284	-0.0626	0.5087		
Mode	1.5357	1.1312	1.3787	1.1564	1.2101			
Max	2.8462			2.7515	8.5258	2.2486		
Alpha					5.9756			
Beta					29.6004			
Data Count	46	% < 0 =	0.45%	None	0.00%	None		
Standard Error	Sample	LogNormal	Normal	Triangular	Beta	Uniform		
Rank	Mean	1.1426	1.1447	1.1426	1.1426	1.1430	1.1426	
SEE / Fit Mean	StdDev	0.3350	0.3225	0.3226	0.3144	0.3219	0.2969	
Chi^2 Fit test	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	0.1112	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 (100%)	Good (100%)	Poor (2%)	Poor (1%)	Poor (2%)





Percent Growth by Milestone

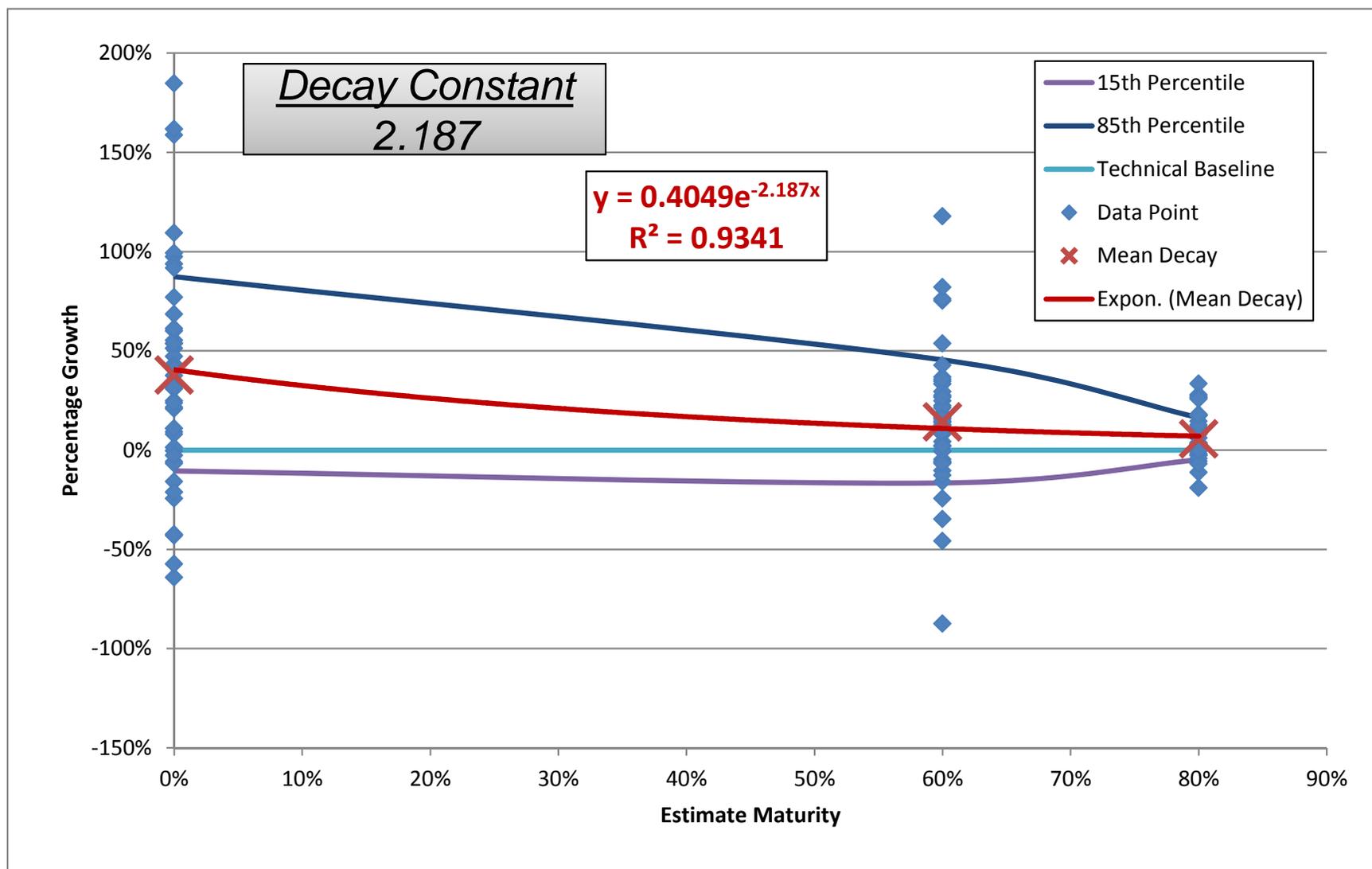
Common Milestones – CADRe Data





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