Historical Mass, Power, Schedule & Cost Growth for NASA Instruments & Spacecraft

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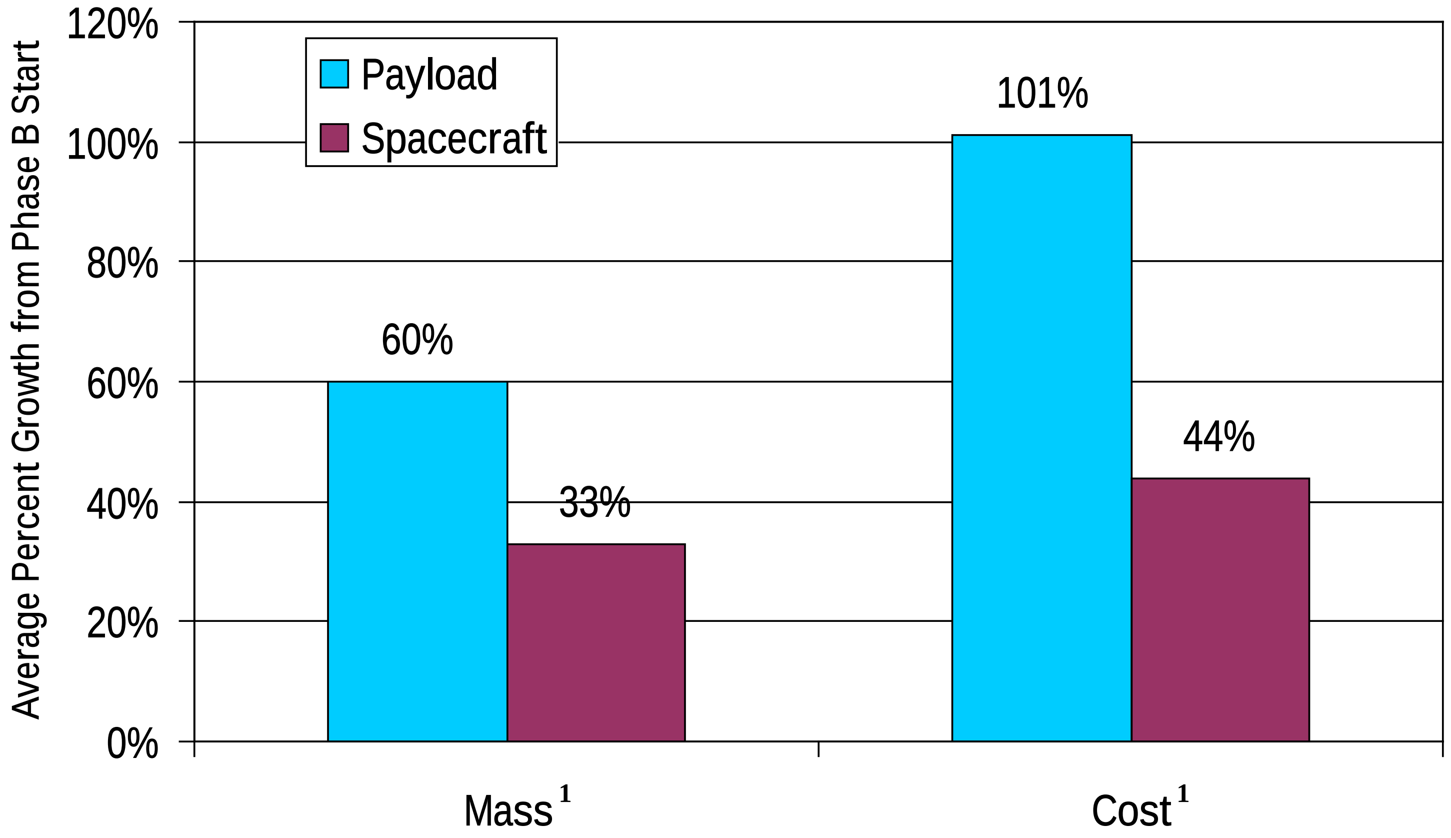
Agenda

- Background
- Instrument Data Overview
- Instrument Growth
- Spacecraft Data Overview
- Spacecraft Growth
- Comparison to Guidelines/ Recommendations
- Summary

Historical NASA Data Indicates Payload Mass and Cost Growth Significantly Greater than Spacecraft Mass & Cost Growth



Data Indicated Payload Resource has Greater Uncertainty than Spacecraft

Note: 1) As measured from Current Best Estimate, not including reserves

* Taken from "Inherent Optimism In Early Conceptual Designs and Its Effect On Cost and Schedule Growth: An Update", Freaner C., Bitten R., Emmons D., 2010 NASA PM Challenge, Houston, Texas, 9-10 February 2010

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Instrument Growth Introduction

- Science instruments are typically the most immature part of any NASA mission development
- As the building of spacecraft become less challenging for a mature industry, NASA's continual need to push the cutting edge of science requires the revolutionary and evolutionary development of instruments to meet science requirements
- Because of this challenge, however, instruments run into substantial issues that result in significant increases in mass, power, cost and schedule
- Although previous studies have identified such issues, there are no industry standard reserve/contingency design and programmatic guidelines for instruments
- This study investigates the historical mass, power, cost and schedule growth of NASA science instruments to more fully understand the growth throughout a mission's lifecycle

Large Diversity of Missions Included in Analysis

- The data set used for the study represents 80 instruments covering 30 missions launched since 1999
- The missions include instrument data collected from:
  - *8 Astrophysics,*
  - *5 Heliophysics,*
  - *7 Earth Science, and*
  - *10 Planetary missions*
- The missions provide a fairly robust representation of different instrument types and science objectives
- Collected data at primary historical milestones KDP-B or Start of Phase B, PDR, CDR and Final Actual at Launch

Mission	Science Type	Launch Year	Instruments Collected
Terra	Earth Science	1999	3
EO-1	Earth Science	2000	1
WMAP	Astrophysics	2001	1
ICESat	Earth Science	2003	1
Spitzer	Astrophysics	2003	3
GALEX	Astrophysics	2003	1
SWIFT	Astrophysics	2004	3
MESSENGER	Planetary	2004	7
MRO	Planetary	2005	6
Deep Impact	Planetary	2005	3
CloudSat	Earth Science	2006	1
STEREO	Heliophysics	2006	4
CALIPSO	Earth Science	2006	1
New Horizons	Planetary	2006	6
Dawn	Planetary	2007	1
Phoenix	Planetary	2007	4
AIM	Heliophysics	2007	3
Fermi	Astrophysics	2008	2
IBEX	Heliophysics	2008	2
Kepler	Astrophysics	2009	1
WISE	Astrophysics	2009	1
OCO	Earth Science	2009	1
LRO	Planetary	2009	6
Juno	Planetary	2011	6
GRAIL	Planetary	2011	1
NuSTAR	Astrophysics	2012	1
RBSP	Heliophysics	2012	4
LDCM	Earth Science	2013	2
IRIS	Heliophysics	2013	1
MAVEN	Planetary	2013	3

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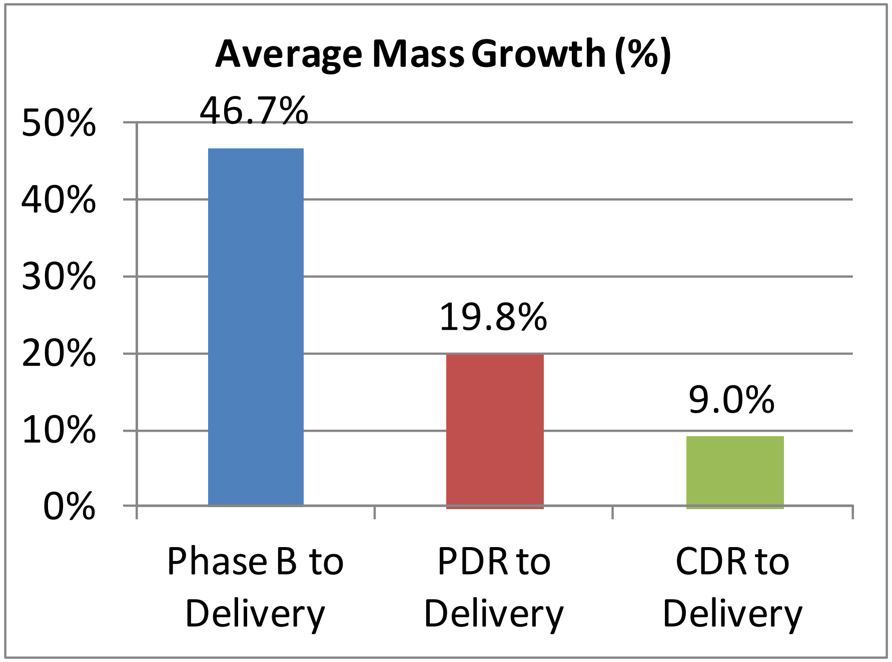
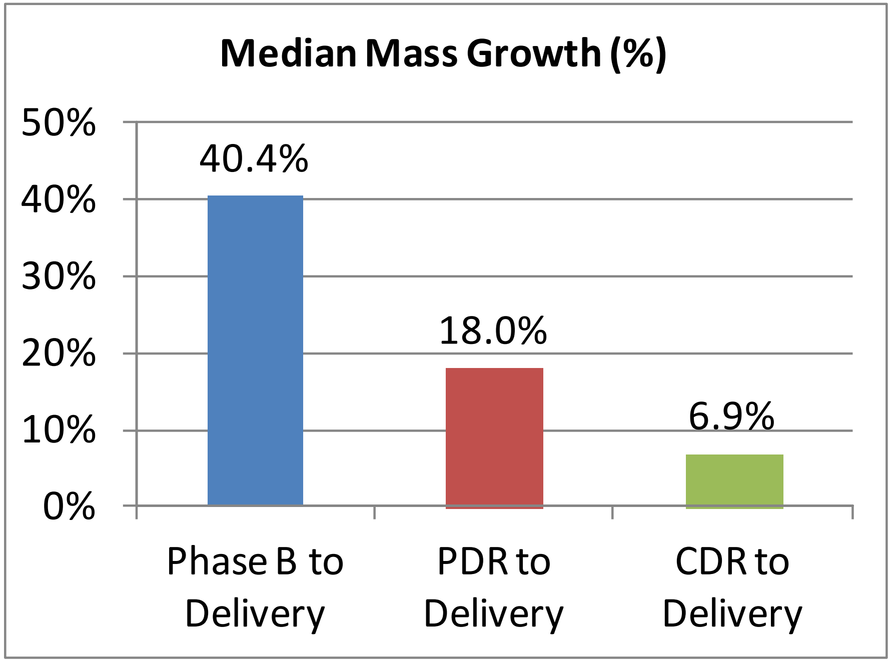
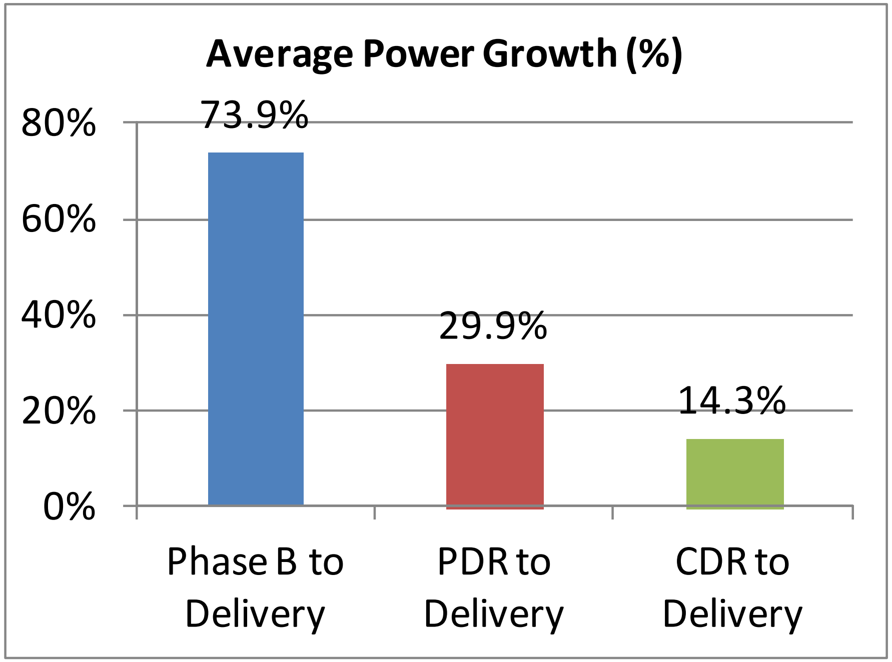
Instrument Mass Growth by Milestone

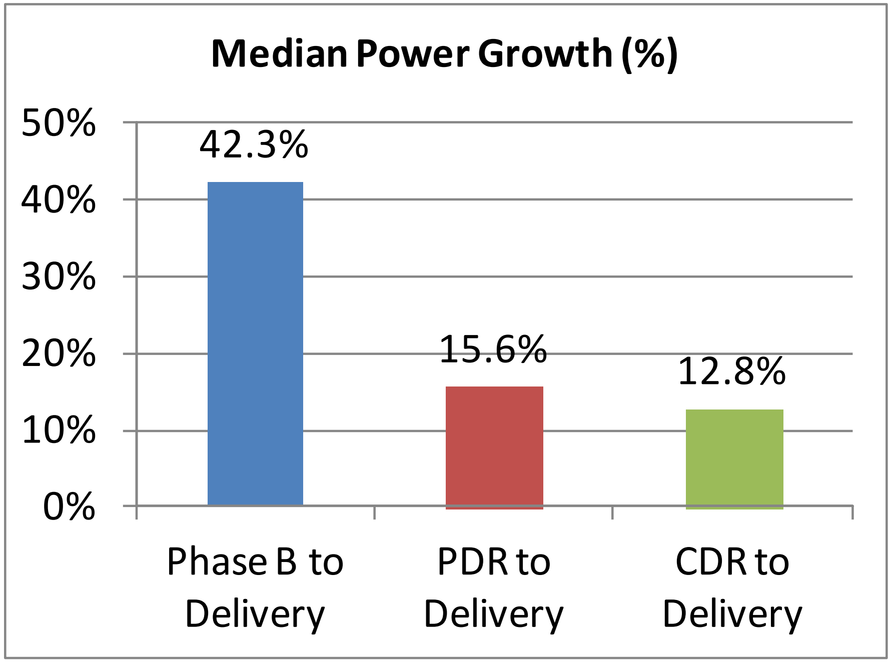




Mass growth percentage reduces as design matures

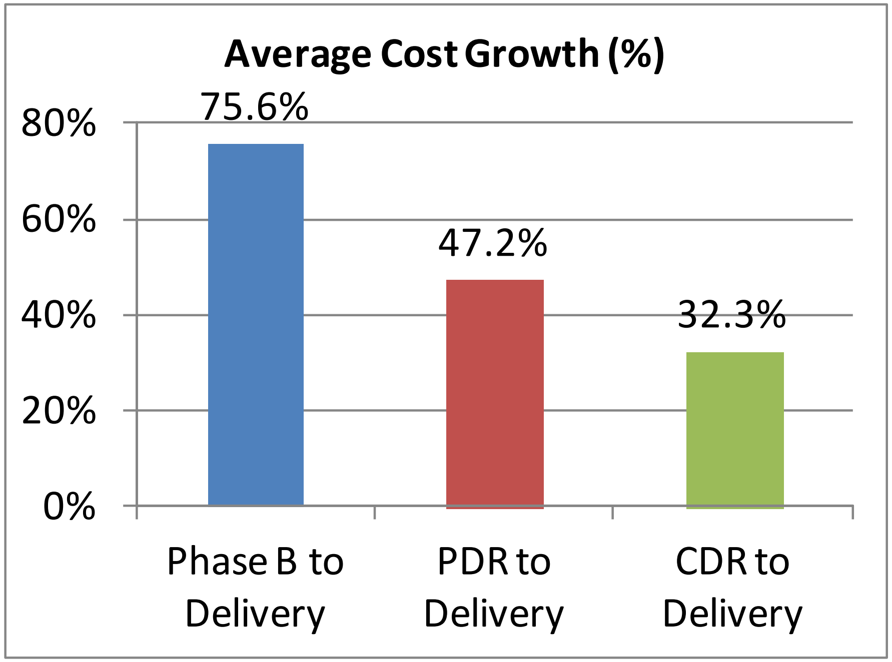
Instrument Power Growth by Milestone

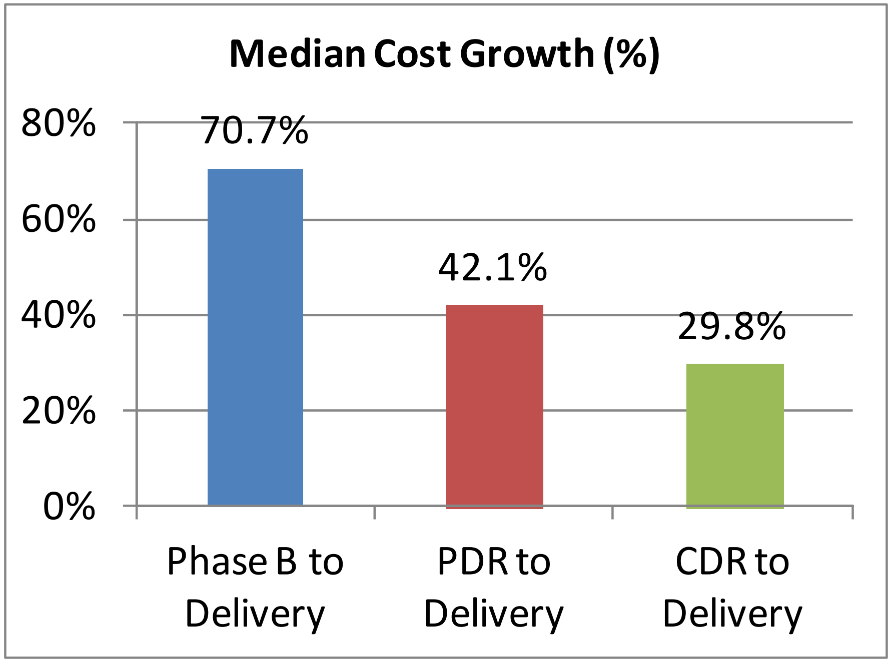




Power growth percentage also reduces as design matures;
Median growth is substantially different than average growth

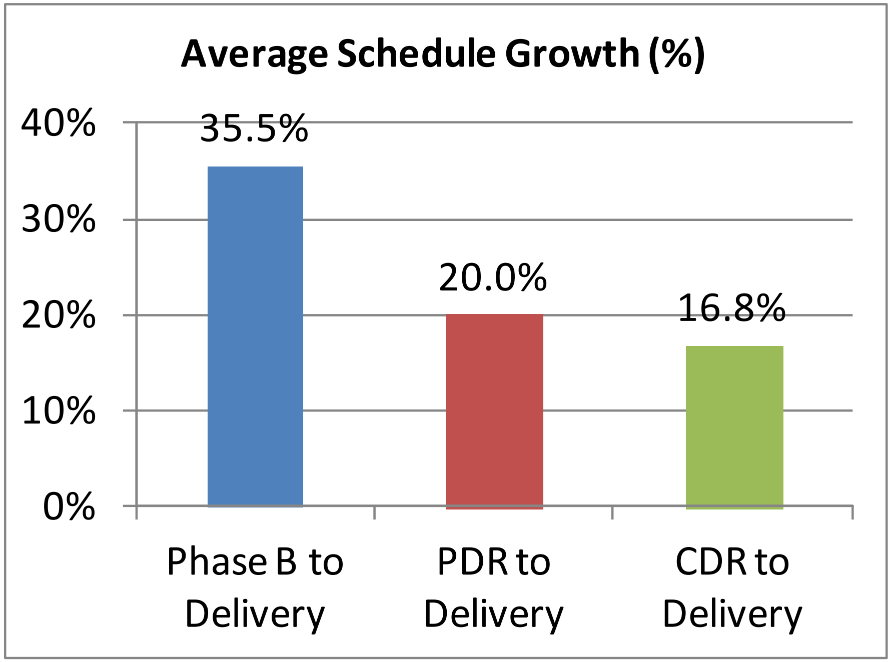
Instrument Cost Growth by Milestone

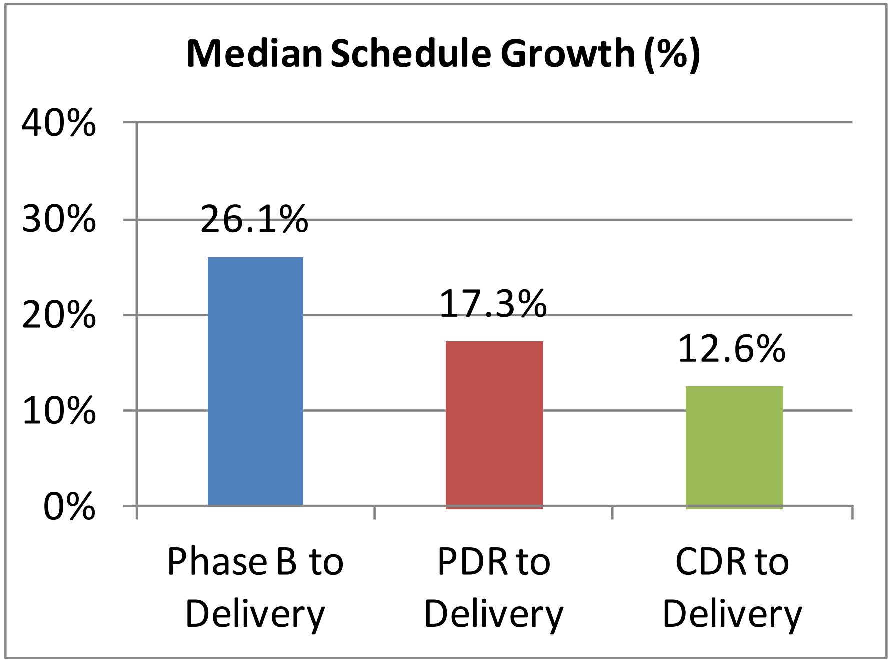




Cost growth percentage does not reduce as much as design matures
Demonstrated by substantial uncertainty still existing at CDR

Instrument Schedule Growth by Milestone





Schedule growth percentage also decreases as design matures

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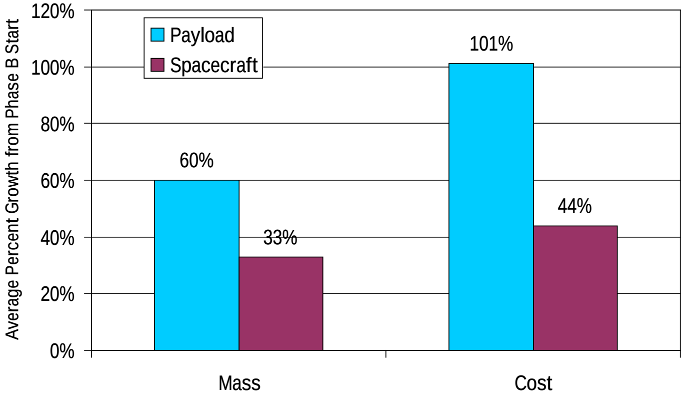
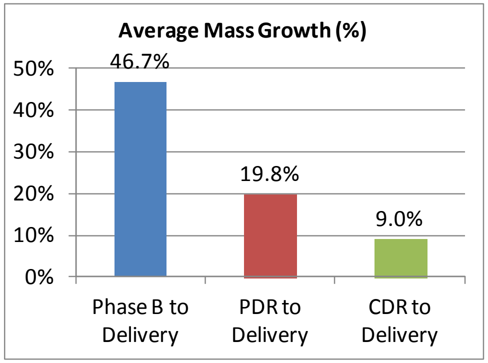
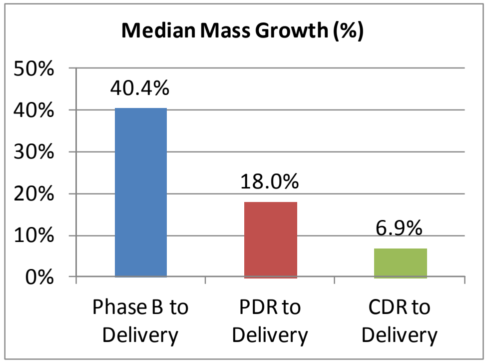
Spacecraft Growth Introduction

- For the past several decades, industry spacecraft developers have been moving towards standardized product lines that satisfy the needs of multiple customer bases and missions
- More standardized bus designs appeal to customers for potential savings in cost and schedule, reduced design uncertainty, and also increased reliability from high heritage designs
- Often customer needs require additional modification of the standardized design, especially in the case of NASA and other government agency customers
- The modification of existing designs or addition of new designs naturally leads to greater overall uncertainty in the design and potential for growth of spacecraft resources over time
- This study assesses historical mass, power, cost, and schedule growth for multiple NASA spacecraft buses from the last twenty years and compares to industry reserve guidelines to understand where the guidelines may fall short

Spacecraft Study Builds from Previous Research







2010 research* indicated that payload resources had greater uncertainty than spacecraft

2014 research** examined instrument growth in depth at the start of Phase B, PDR, and CDR milestones

*"Inherent Optimism In Early Conceptual Designs and Its Effect On Cost and Schedule Growth: An Update", Freaner C., Bitten R., Emmons D., 2010 NASA PM Challenge, Houston, Texas, 9-10 February 2010

**"Historical mass, power, schedule, and cost growth for NASA science instruments," R. Bitten and S. A. Shinn, 2014 IEEE Aerospace Conference, 2014, pp. 1–10.

This study*** examines growth of spacecraft buses in depth at the start of Phase B, PDR, and CDR milestones similar to what was performed for instruments

Additionally, a comparison of NASA in-house and Rapid Spacecraft Development Office (RSDO) catalog buses has been performed

Analysis of spacecraft subsystem growth is also presented

Calculated growth for mass, power, cost, or schedule from each milestone, PDR for example, is calculated as:

$$Growth\ from\ PDR = \frac{(Final - CBE@PDR)}{CBE@PDR}$$

where:

- CBE@PDR represents the current best estimate without reserves for the total mass, power, cost, or schedule at PDR (total cost/schedule, not cost/schedule to go) and
- final value represents the final total mass, power, cost, or schedule at delivery/launch

***M. R. Hayhurst, D. C. Judnick, R. E. Bitten, I. E. Hallgrimson, S. A. Shinn and M. A. Youngs, "Historical mass, power, schedule, and cost growth for NASA spacecraft," 2016 IEEE Aerospace Conference, Big Sky, MT, 2016, pp. 1-17.

Large Diversity of Missions Included in Analysis

- Missions used in the study include 47 spacecraft bus developments launched since 1996

Missions represent NASA science themes
- 10 Astrophysics
- 8 Heliophysics
- 12 Earth Science
- 16 Planetary

Mission	Science Type	Launch Year	Mission	Science Type	Launch Year
NEAR	Planetary	1996	Dawn	Planetary	2007
Cassini	Planetary	1997	Fermi	Astrophysics	2008
TRMM	Earth Science	1997	IBEX	Heliophysics	2008
Stardust	Planetary	1999	OCO	Earth Science	2009
Landsat 7	Earth Science	1999	Kepler	Astrophysics	2009
Terra	Earth Science	1999	LRO	Planetary	2009
EO-1	Earth Science	2000	WISE	Astrophysics	2009
WMAP	Astrophysics	2001	SDO	Heliophysics	2010
Genesis	Planetary	2001	Glory	Earth Science	2011
RHESSI	Heliophysics	2002	Juno	Planetary	2011
ICESat	Earth Science	2003	GRAIL	Planetary	2011
GALEX	Astrophysics	2003	Suomi NPP	Earth Science	2011
MER	Astrophysics	2003	MSL	Planetary	2011
Spitzer	Astrophysics	2003	NuSTAR	Astrophysics	2012
MESSENGER	Planetary	2004	RBSP	Heliophysics	2012
Swift	Astrophysics	2004	LDCM	Earth Science	2013
Deep Impact	Planetary	2005	IRIS	Astrophysics	2013
MRO	Planetary	2005	LADEE	Planetary	2013
New Horizons	Planetary	2006	MAVEN	Planetary	2013
CloudSat	Earth Science	2006	GPM	Earth Science	2014
STEREO	Heliophysics	2006	OCO-2	Earth Science	2014
THEMIS	Heliophysics	2007	SMAP	Earth Science	2014
AIM	Heliophysics	2007	MMS	Heliophysics	2015
Phoenix	Planetary	2007			

Missions provide a fairly robust representation of different science objectives that influence bus design

- Collected data at primary historical milestones KDP-B or Start of Phase B, PDR, CDR and Final Actual at Launch
  - *Not all missions have data available at every milestone so some analyses have fewer than 47 data points*
  - *For missions with multiple identical spacecraft, the first build was examined*
  - *For landed missions, the cruise stage was considered as the spacecraft bus*

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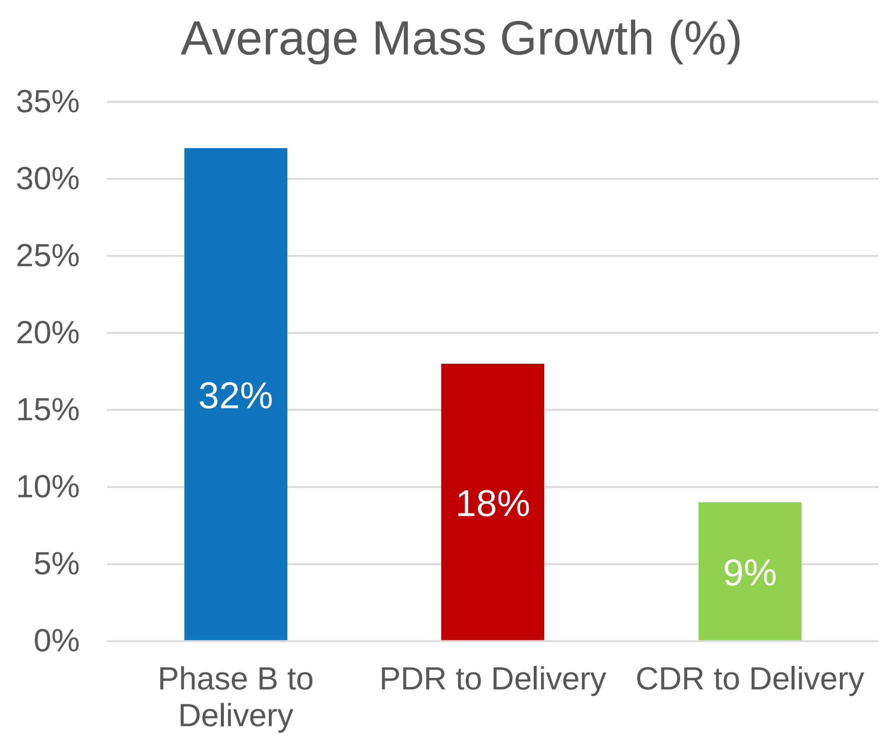
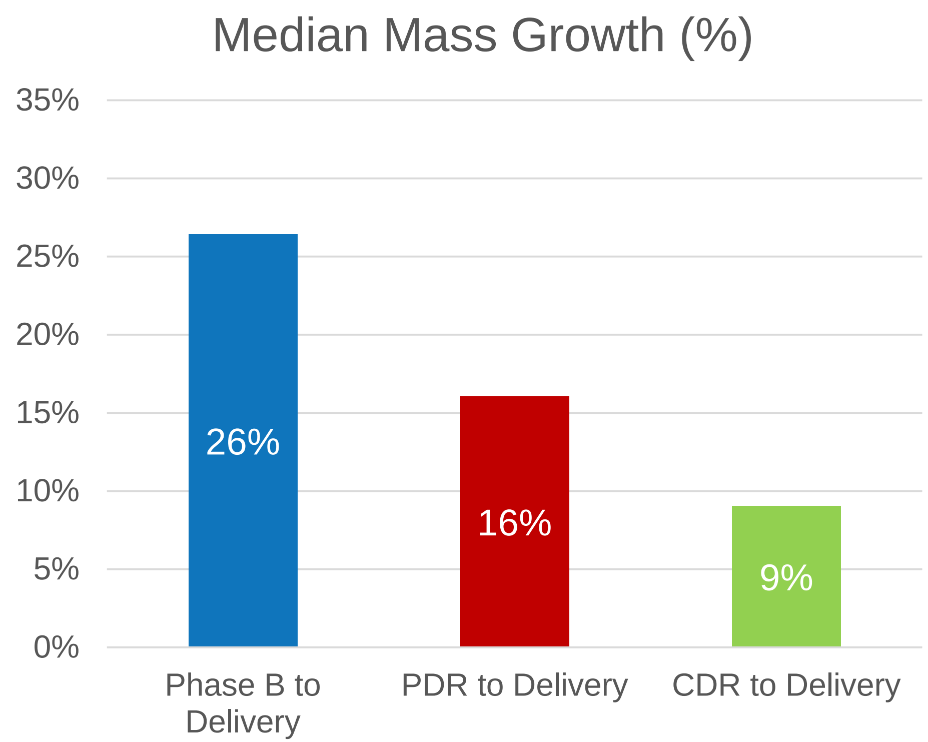
Spacecraft Mass Growth by Milestone

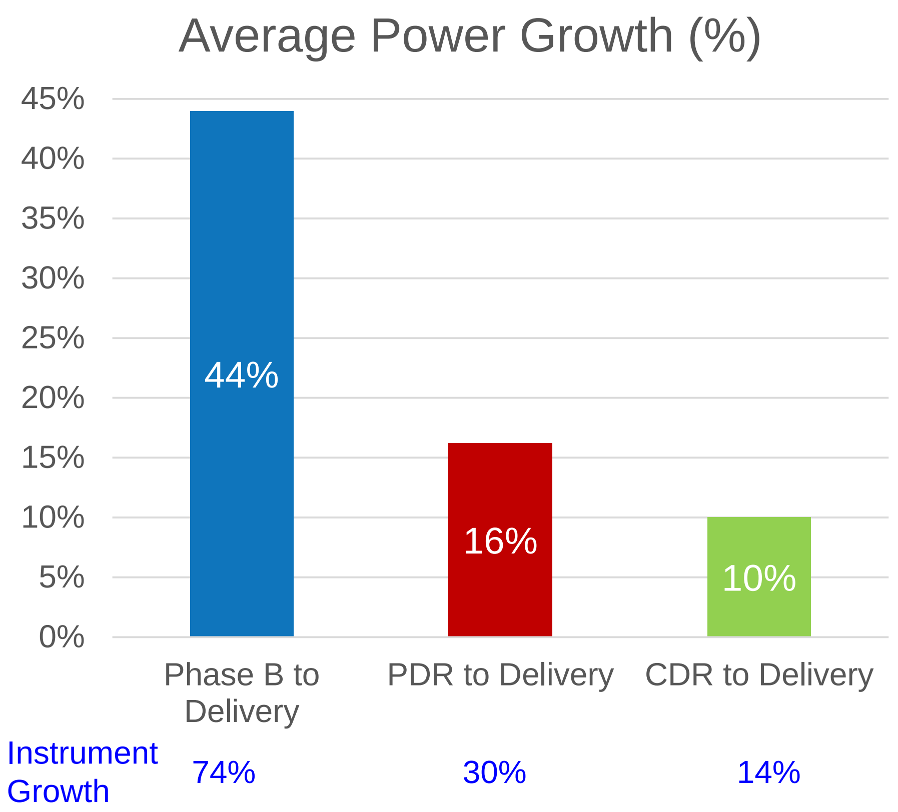


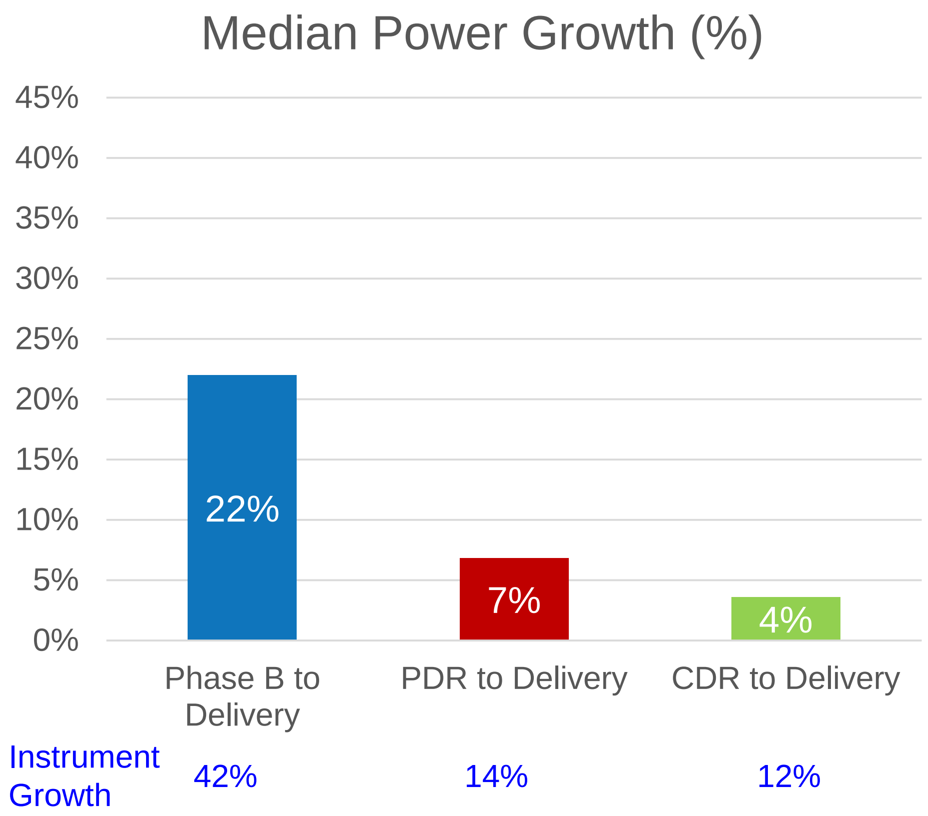


	Phase B to Delivery	PDR to Delivery	CDR to Delivery
Instrument Growth (average)	48%	20%	9%
Instrument Growth (median)	40%	18%	7%

Mass growth shrinks by about 10% on average every milestone
Spacecraft growth is significantly less than instruments at start of Phase B

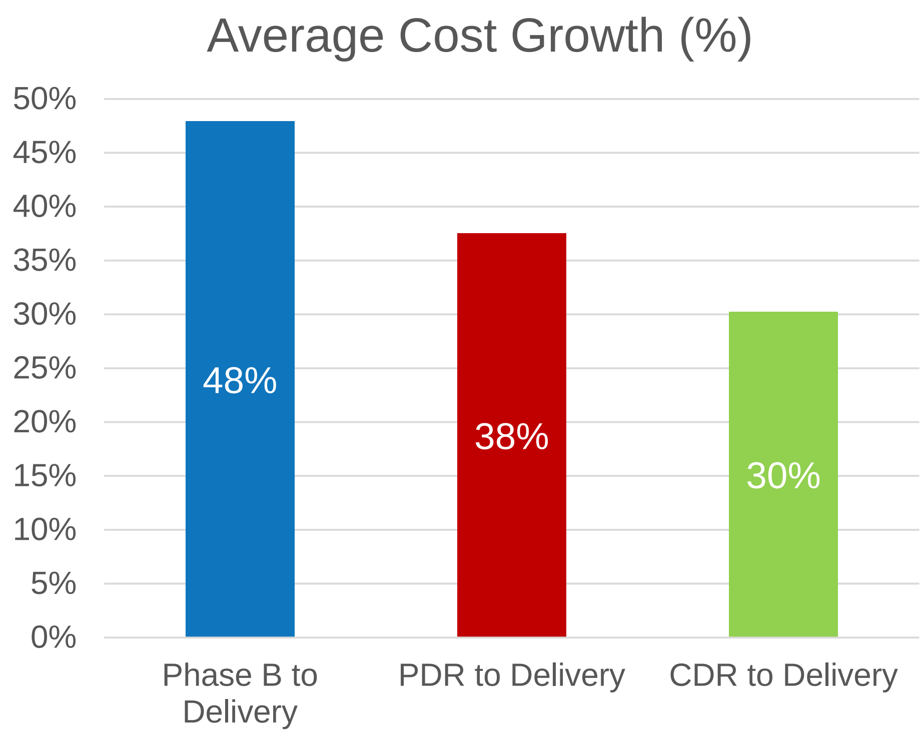
Spacecraft Power Growth by Milestone



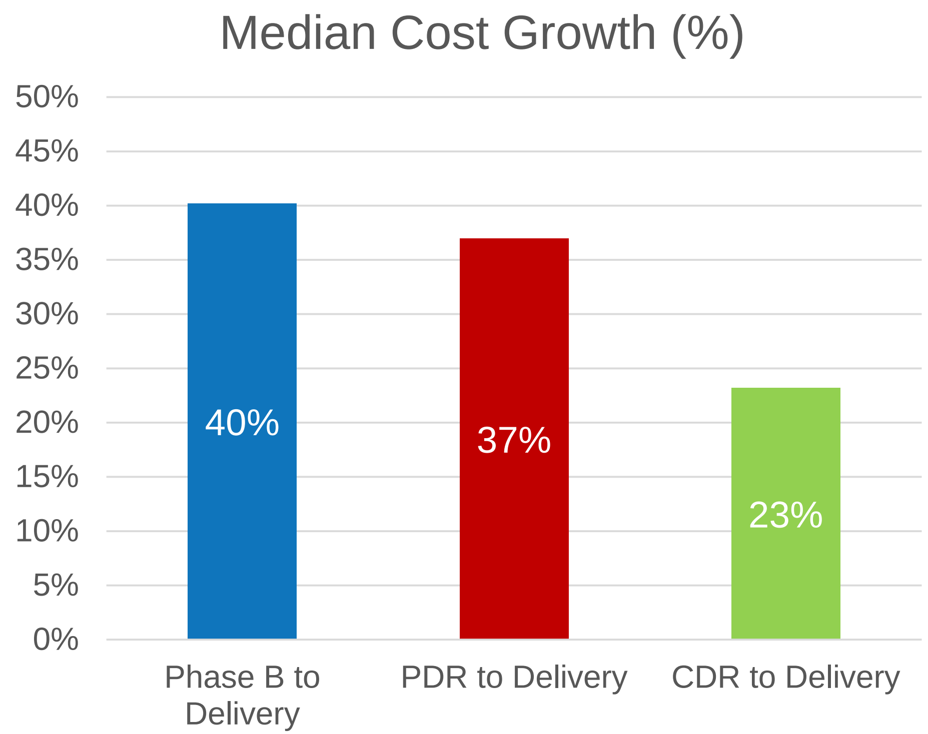


Power growth reduces as design matures and is significantly reduced by the CDR
Spacecraft power growth lower than instruments at all milestones

Spacecraft Bus/I&T Cost Growth by Milestone



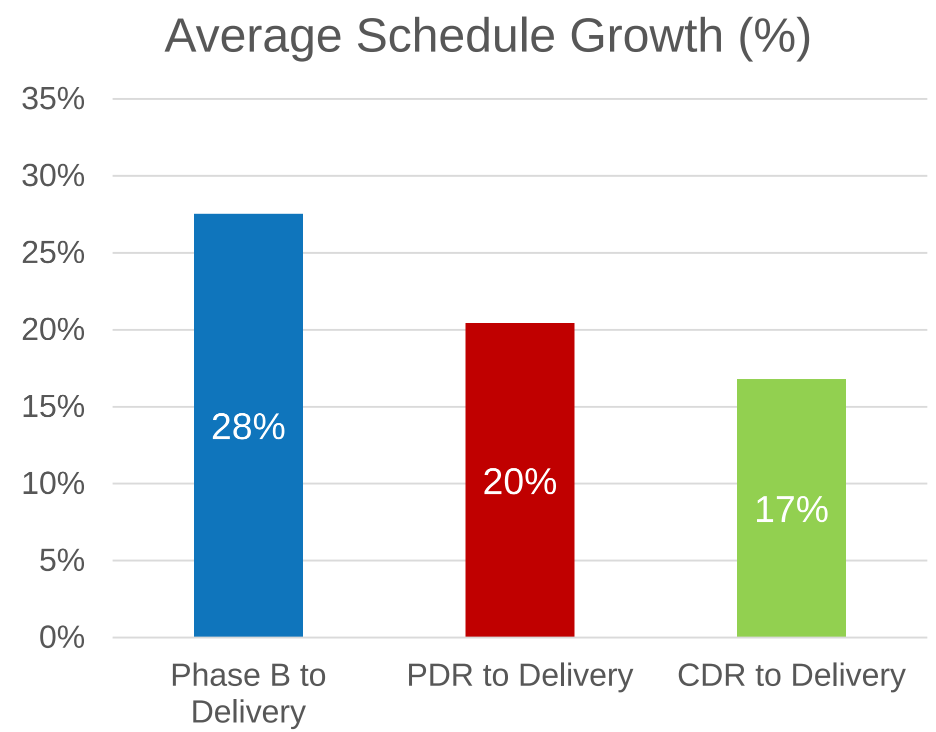
Instrument Growth: 76% | 46% | 32%

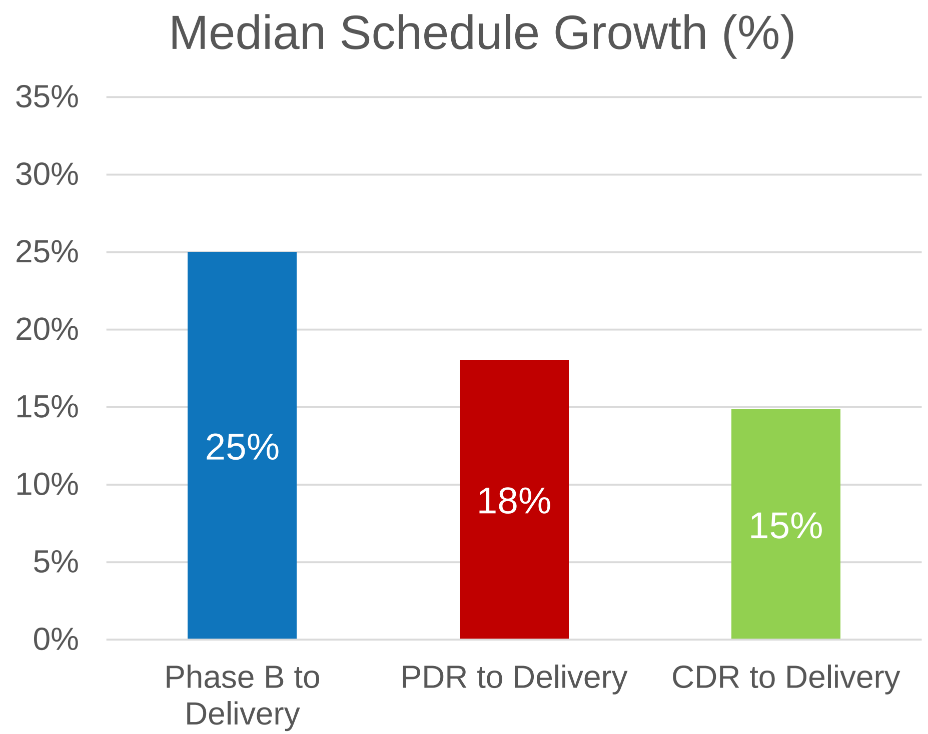


Instrument Growth: 71% | 39% | 30%

Cost growth does not reduce significantly as substantial uncertainty remains at CDR
Spacecraft growth is lower than instruments at start of Phase B

Spacecraft Bus Schedule Growth by Milestone

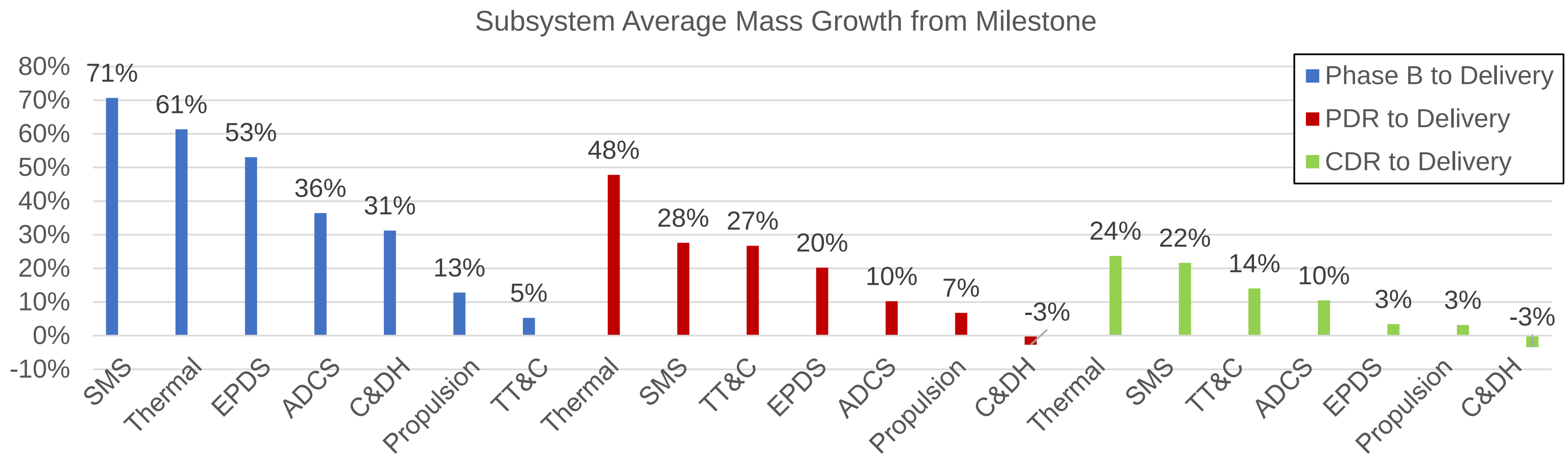


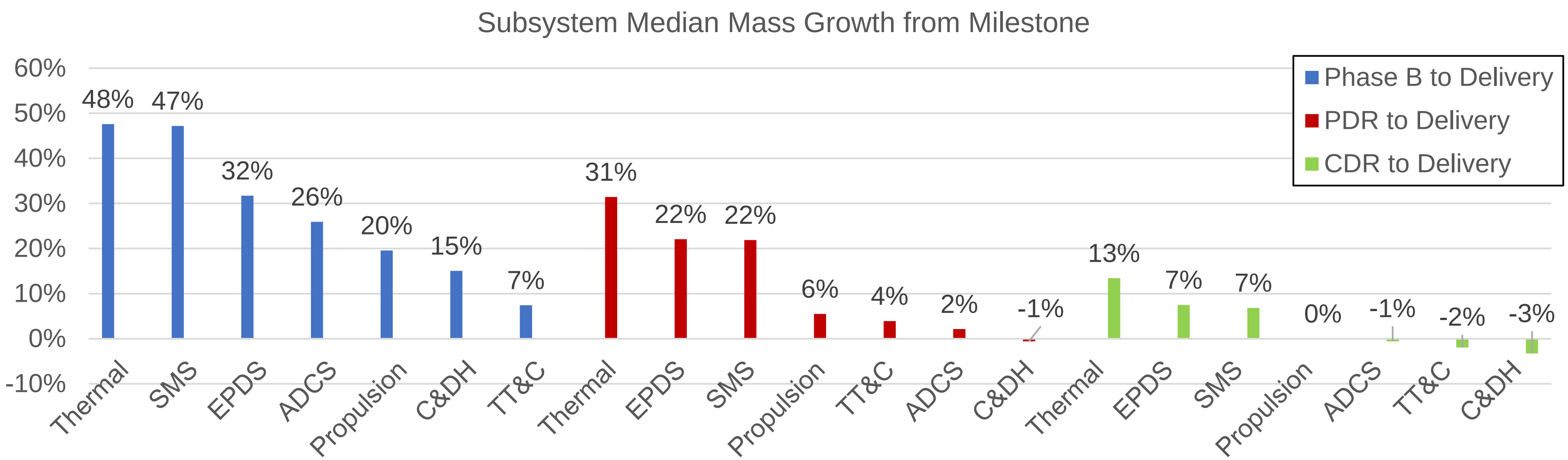


	Phase B to Delivery	PDR to Delivery	CDR to Delivery
Instrument Growth (Average)	36%	20%	17%
Instrument Growth (Median)	27%	17%	13%

Similar to cost, schedule growth does not reduce as significantly by CDR
Spacecraft schedule growth appears in family with instruments

Spacecraft Bus Subsystem Mass Growth by Milestone





"Interconnected" systems appear to have the highest growth: Thermal, EPDS (Harness), SMS (Brackets/Support Structure)
"Box-like" systems appear to have the lowest growth: C&DH, TT&C, ADCS

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Example Reserve Discussion References

- "Goddard Space Flight Center Rules for the Design, Development, Verification, and Operation of Flight Systems," GSFC-STD-1000F, February 2013.
- "Goddard Space Flight Center Rules for the Design, Development, Verification, and Operation of Flight Systems," GSFC-STD-1000E, August 2009
- GSFC Goddard Procedural Requirement (GPR) 7120.7 "Schedule Margins and Budget Reserves to be used in Planning Flight Projects and in Tracking Their Performance," May 2008
- NASA Mission Design Process, An Engineering Guide to the Conceptual Design, Mission Analysis, and Definition Phases, The NASA Engineering Management Council, December 22, 1992
- JPL Design Principles, Design, Verification/ Validation and Operations Principles for Flight Systems (D-17868), Rev. 2, March 3, 2003
- ANSI/AIAA Guide for Estimating and Budgeting Weight and Power Contingencies for Spacecraft Systems, AIAA-G-020-1992, April 16, 1992
- "Mass Properties Control for Space Systems Draft for Public Review", AIAA S-120A-2015, 2015.
- "Mass Properties Control for Space Systems", AIAA S-120-2006, December 2006
- "JSC Cost Estimating Handbook Cost Reserve Guidelines", http://www1.jsc.nasa.gov/bu2/guidelines.html.

Instrument Mass & Power Contingency vs. Growth

Mass Contingency Guidelines

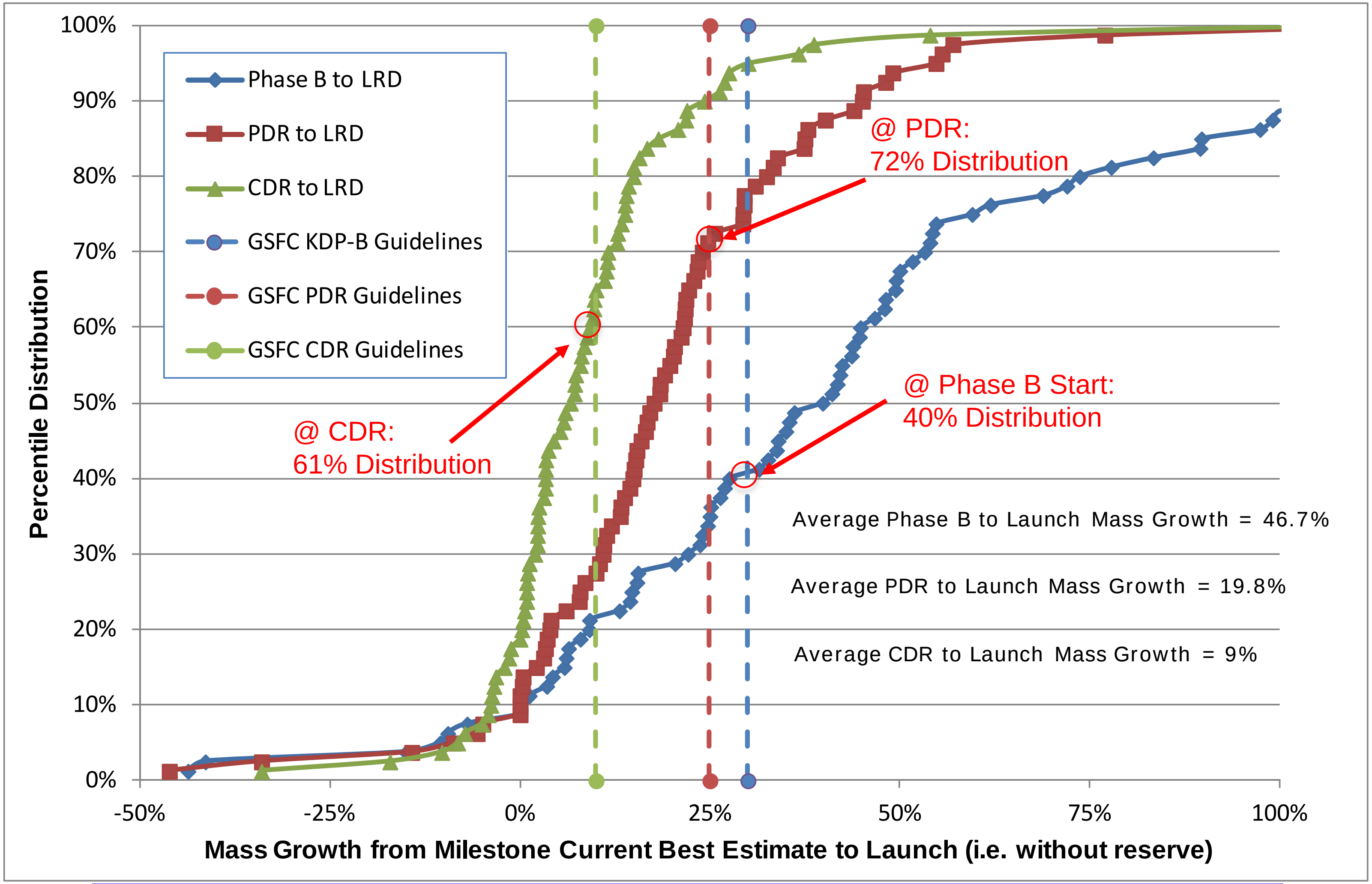
Source	Relative to:	Phase B Start	At PDR	At CDR
Historical Median Growth	**Instrument**	**40%**	**18%**	**7%**
NASA "Green Book" [7]	**Flight System**	**35%**	**30%**	**25%**
Goddard Gold Rules [8]	**Instrument**	**30%**	**25%**	**10%**
JPL Design Principles [9]	**Flight System**	**30%**	**20%**	**10%**
AIAA Standard [10]	**Instrument**	**30%**	**25%**	**10%**

Power Contingency Guidelines

Source	Relative to:	Phase B Start	At PDR	At CDR
Historical Median Growth	**Instrument**	**42%**	**16%**	**13%**
NASA "Green Book" [7]	**Flight System**	**35%**	**30%**	**20%**
Goddard Gold Rules [8]	**Flight System**	**25%**	**15%**	**15%**
JPL Design Principles [9]	**Flight System**	**30%**	**20%**	**15%**
AIAA Standard [12]	**Instrument**	**65%**	**40%**	**15%**

Historical Mass & Power growth percentage at Phase B Start typically higher than guidelines while PDR & CDR are more in line

Instrument Mass Growth by Milestone



Mass growth percentage reduces as design matures

Instrument Cost & Schedule Contingency vs. Growth

Cost Contingency Guidelines

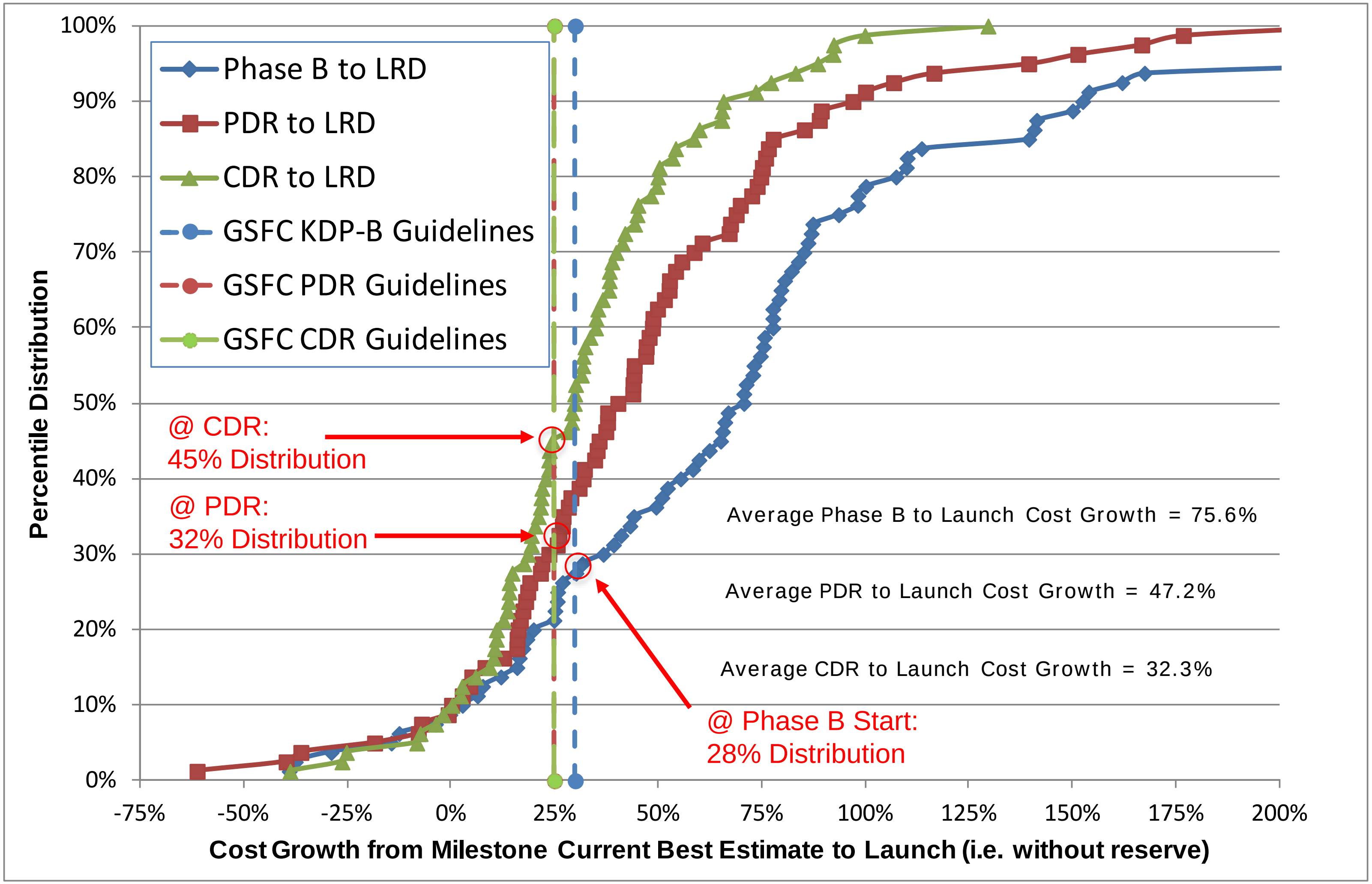
Source	Relative to:	Phase B Start	At PDR	At CDR
Historical Median Growth	**Instrument**	**71%**	**42%**	**30%**
NASA "Green Book" [7]	**Mission**	**35%**	**30%**	**20%**
GSFC GPR 7120.7 [13]	**Mission**	**30%**	**25%**	**25%**
JPL Design Principles [9]	**Mission**	**30%**	**25%**	**20%**
JSC Cost Handbook [14]	**Flight System**	**35-50%**	**25%**	**20%**

Schedule Contingency Guidelines

Source	Relative to:	Phase B Start	At PDR	At CDR
Historical Median Growth	**Instrument**	**26%**	**17%**	**13%**
NASA "Green Book" [7]	**Mission**	**15%**	**10%**	**10%**
GSFC GPR 7120.7 [13]	**Mission**	**10%**	**10%**	**8%**
JPL Design Principles [9]	**Mission**	**10%**	**10%**	**8%**
Industry Rule of Thumb	**Mission**	**8%**	**8%**	**8%**

Historical Cost & Schedule growth percentages are significantly higher than guidelines at most milestones

Instrument Cost Growth by Milestone



Cost growth percentage also reduces as design matures but is mostly above guidelines

Spacecraft Mass & Power Contingency vs. Growth

Mass Contingency Guidelines

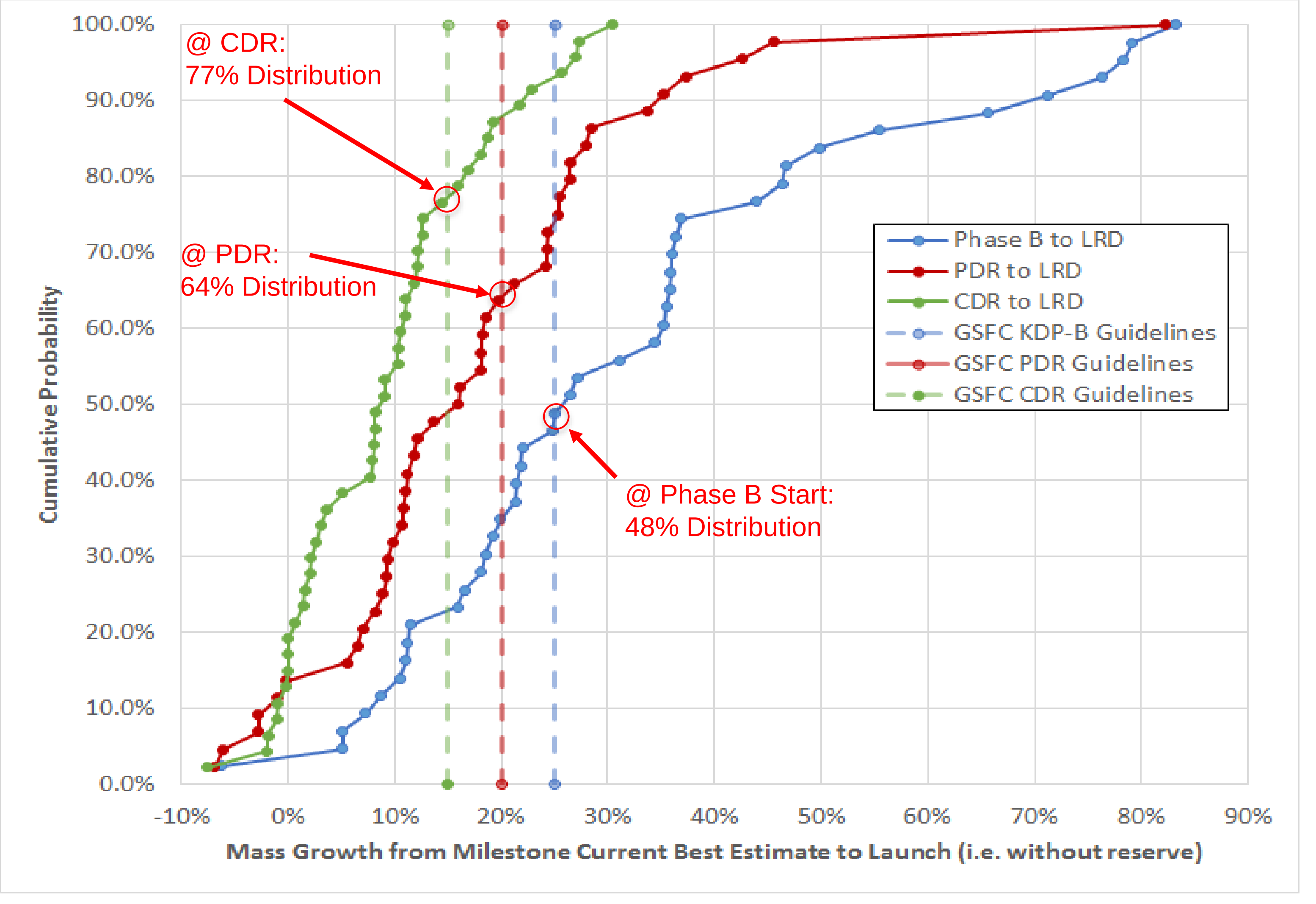
Source	Relative to:	Phase B Start	At PDR	At CDR
Historical Med. Growth	**Spacecraft**	**26%**	**16%**	**9%**
Historical Avg. Growth	**Spacecraft**	**32%**	**18%**	**9%**
NASA "Green Book" [6]	**Flight System**	**35%**	**30%**	**25%**
Goddard Gold Rules [7]	**Flight System**	**25%**	**20%**	**15%**
JPL Design Principles [8]	**Flight System**	**30%**	**20%**	**10%**
AIAA Standard [9]	**Flight System**	**30%**	**21%**	**12%**

Power Contingency Guidelines

Source	Relative to:	Phase B Start	At PDR	At CDR
Historical Med. Growth	**Spacecraft**	**22%**	**7%**	**4%**
Historical Avg. Growth	**Spacecraft**	**44%**	**16%**	**10%**
NASA "Green Book" [6]	**Flight System**	**35%**	**30%**	**20%**
Goddard Gold Rules [7]	**Flight System**	**25%**	**20%**	**15%**
JPL Design Principles [8]	**Flight System**	**30%**	**20%**	**15%**
AIAA Standard [10]	**Flight System**	**22%**	**15%**	**10%**

Guidelines appear mostly adequate compared to historical mass & power growth

Spacecraft Bus Mass Growth by Milestone



Spacecraft Cost & Schedule Contingency vs. Growth

Cost Contingency Guidelines

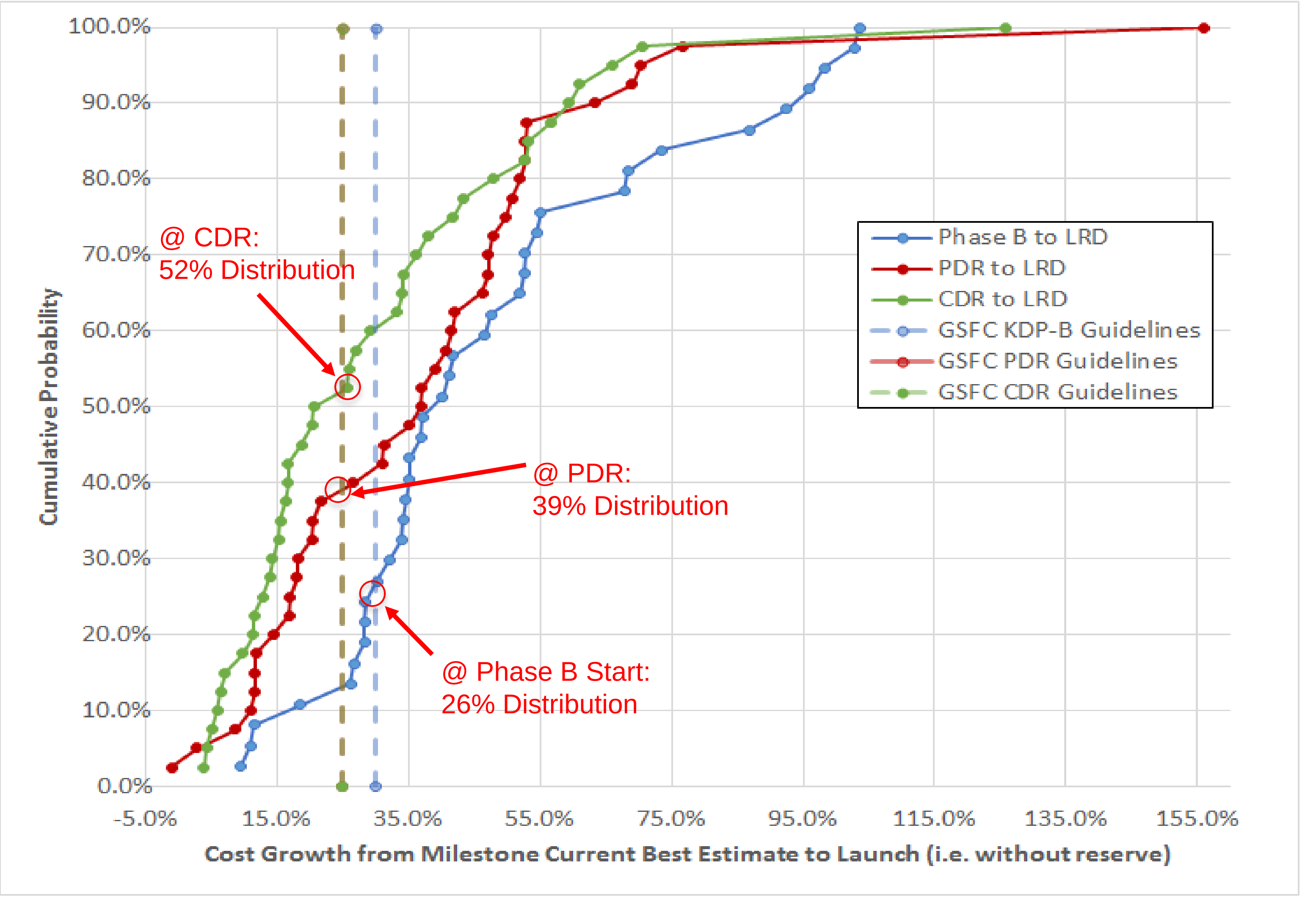
Source	Relative to:	Phase B Start	At PDR	At CDR
Historical Med. Growth	**Spacecraft**	**40%**	**37%**	**23%**
Historical Avg. Growth	**Spacecraft**	**48%**	**38%**	**30%**
NASA "Green Book" [6]	**Mission**	**35%**	**30%**	**20%**
GSFC GPR 7120.7 [11]	**Mission**	**30%**	**25%**	**25%**
JPL Design Principles [8]	**Mission**	**30%**	**25%**	**20%**
JSC Cost Handbook (Within SOTA) [12]	**Flight System**	**35%**	**25%**	**20%**
JSC Cost Handbook (Beyond SOTA) [12]	**Flight System**	**50%**	**25%**	**20%**

Schedule Contingency Guidelines

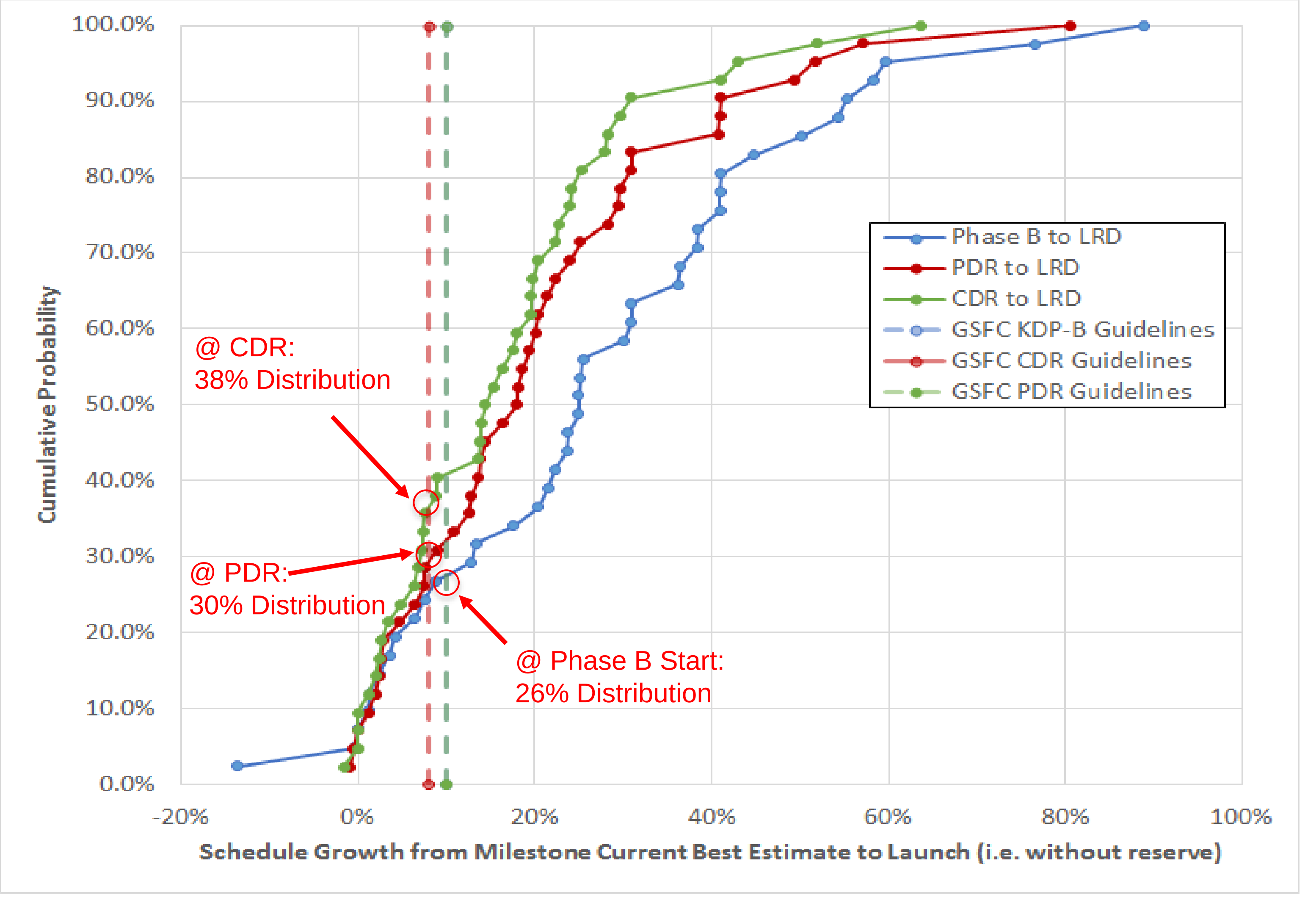
Source	Relative to:	Phase B Start	At PDR	At CDR
Historical Med. Growth	**Spacecraft**	**25%**	**20%**	**17%**
Historical Avg. Growth	**Spacecraft**	**28%**	**20%**	**17%**
NASA "Green Book" [6]	**Mission**	**15%**	**10%**	**10%**
GSFC GPR 7120.7 [11]	**Mission**	**10%**	**10%**	**8%**
JPL Design Principles [8]	**Mission**	**10%**	**10%**	**8%**
Industry Rule of Thumb	**Mission**	**8%**	**8%**	**8%**

Historical cost & schedule growth percentages are significantly higher than guidelines at most milestones

Spacecraft Bus Cost Growth by Milestone



Spacecraft Bus Schedule Growth by Milestone



Instrument Recommendations

- Data indicates that instrument designs are typically immature at the start of Phase B
- There is a need to guard against growth and/or increase the maturity levels of the instrument prior to mission Phase B start
- This may be accomplished by:
  - *Significantly increasing mass, power, cost and schedule reserve beyond current guidelines*
  - *Perform analogous technical comparison of in-family instruments so as to help more conservatively scope the initial mass, power, cost and schedule resources*
  - *Start development of the instrument prior to mission Phase B start so as to increase the maturity of the instrument before mission development begins*

Maturing Instrument Prior to Mission Phase B Start

- A potential alternative consideration, developed by the NASA Earth Science Technology Office (ESTO), is to start the instrument development prior to mission start - entitled an Instrument First, Spacecraft Second (IFSS) approach – which brings the instruments to a CDR level of maturity prior to starting a mission
- IFSS has been identified as an approach to significantly reduce the collateral mission cost growth due to instrument delays and results in more missions being funded for less cost when implemented for a portfolio of missions
- Based on the historical data from the study, an IFSS approach would reduce the required reserve levels for instrument development to 10% for mass, 15% for power, 30% for cost, and 20% for schedule at the start of mission development
- This is much more manageable and closer to current industry guidelines for mission development

Resource	@ Instrument CDR
Mass	10%
Power	15%
Cost	30%
Schedule	20%

Spacecraft Recommendations

- The historical mass and power growth data collected for spacecraft and spacecraft subsystems in this analysis and that of our previous work for instruments firstly indicates that that these items behave differently in terms of growth

- However, several of the guidelines only specify single overall reserve values without respect to spacecraft or instrument
  - *The growth of different elements might be better controlled if specific tailored guidelines were implemented at the lower level*
  - *From our analyses we believe there is sufficient data to recommend tailored mass reserve guidelines for the spacecraft, instrument, and spacecraft subsystems*
  - *We also believe that guidelines for power at the spacecraft and instrument levels could be established based on these analyses*

- As we also found previously for instruments, spacecraft bus cost and schedule reserves were well below the actual historical growth found
  - *These guidelines should be increased to reflect actual growth found in this data set*
  - *These reserve levels could also be established at the spacecraft and instrument levels*

Agenda

- Background
- Instrument Data Overview
- Instrument Growth
- Spacecraft Data Overview
- Spacecraft Growth
- Comparison to Guidelines/ Recommendations
- Summary

Summary

- Instrument Study Results
  - *Provided an assessment of the historical mass, power, cost, and schedule growth for 80 NASA instruments from 30 missions*
  - *Results show that instrument growth is significantly higher than industry standard reserve guidelines which generally apply to the overall flight system*
    - Implies a need to identify approaches to offset the historical growth
  - *Increasing the design maturity prior to full mission development may allow instrument required reserve resources to be reduced and to be more in line with the other flight system reserve requirements*

- Spacecraft Study Results
  - *Provided an assessment of the historical mass, power, cost, and schedule growth for 47 NASA spacecraft*
  - *Results show that overall spacecraft level mass and power guidelines are reasonably sufficient but that cost and schedule reserves are insufficient versus historical growth*
    - By PDR and CDR, all bus development efforts appear to experience a comparable level of growth
  - *Larger cost and schedule uncertainties at start of Phase B may help cover cost and schedule growth in early development*