Life Cycle Cost Growth Study
20 Science Mission Directorate (SMD) Missions

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Claude Freaner, Science Mission Directorate, NASA HQ*

* Note: A special acknowledgement to Bob Bitten & Debra Emmons of The Aerospace Corporation for making significant contributions

Background

- Previous studies[1, 2] have primarily examined Development Cost Growth in an attempt to determine when in the development lifecycle the growth occurs
- Growth was studied for 20 SMD Missions launched between 2000 and 2009.
  - Mass, Power, Cost, and Schedule were examined
- Launch vehicle and Phase E operations costs (planned versus actual) have also grown but the amounts/phasing of this growth were not included in the prior studies
  - Current study includes LV and Phase E operations cost

1. "Using Historical NASA Cost and Schedule Growth to Set Future Program and Project Reserve Guidelines", Bitten R., Emmons D., Freaner C., IEEE Aerospace Conference, Big Sky, Montana, March 3-10, 2007
2, "Optimism in Early Conceptual Designs and Its Effect on Cost and Schedule Growth: An Update", Bitten R., Freaner C., Emmons D., 2010 NASA Program Management Challenge, Galveston, Texas, February 9-10, 2010

Study Approach

- For a set of 20 missions in the study, the cost data were obtained from all of the CADRes for missions at ATP (Phase B start), PDR, CDR, and Launch.
- The cost data was "binned" into these Work Breakdown Structure (WBS) element categories:
  - PMSEMA: Project Management, Systems Engineering, Mission Assurance
  - SCI/EPO: Science, Education, Public Outreach
  - Payload
  - Bus/AIT: Spacecraft Bus, System Assembly Integration and Test
  - GDS/MOS: pre-launch Ground Data System, Mission Operations
  - L/V: Launch Vehicle
  - Phase E: Post-Launch Operations and Data Analysis
- Cost data has not been adjusted for "Full Cost" effects
  - Primarily impacts STEREO, CALIPSO, FERMI

The majority of these missions were in development prior to the CADRe requirement existing, so separation of the costs into the standard WBS Level 2 elements was difficult. Therefore, the elements were combined into the above bins.

Database Description:

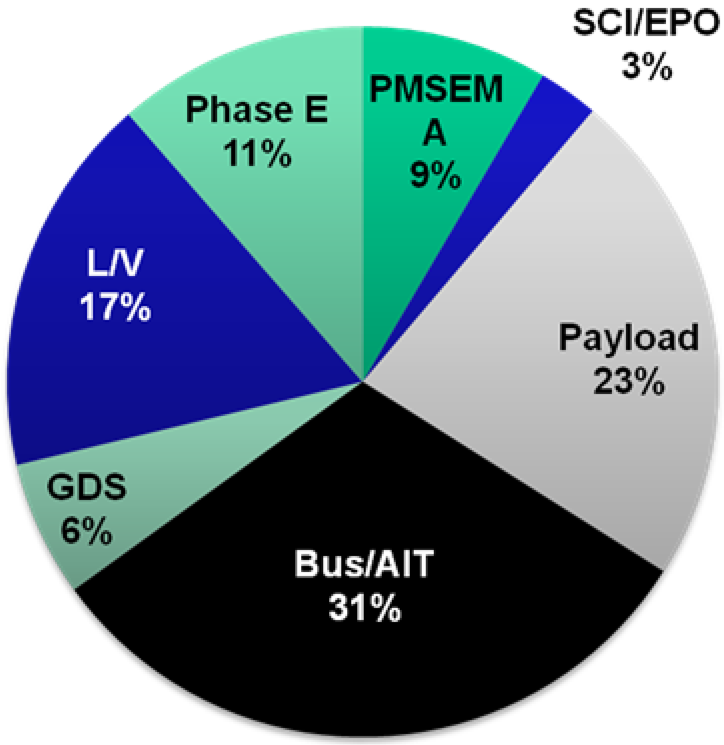
20 Missions Represent a Wide Range of Recent NASA Missions

- 5 Directed vs. 15 Competed missions
- 7 Planetary missions vs. 13 Earth or near-Earth Orbiters
- 7 Planetary Science vs. 5 Astrophysics vs. 5 Earth Science vs. 3 Heliophysics missions

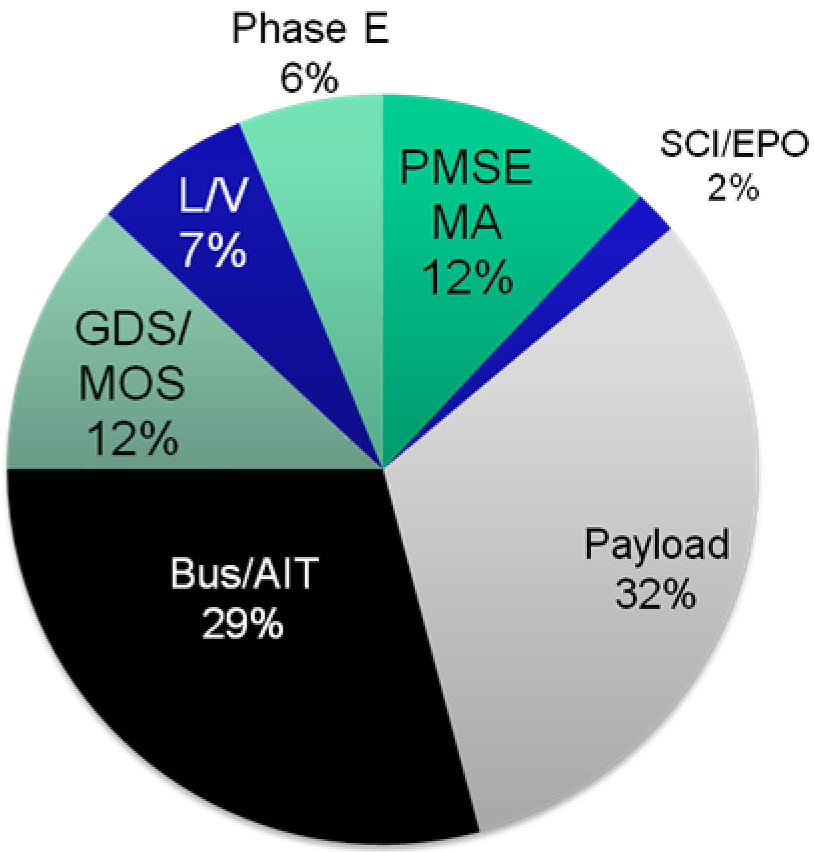
	Planetary?	Program	Science Type	Key Center(s)	Launch Year	Acquisition Type	Number of Instruments	Comments
EO-1		NMP	Earth Science	GSFC	2000	Competed	5	Advanced land imaging technology demonstrator
GENESIS	X	Discovery	Planetary Science	JPL	2001	Competed	4	Collect samples of solar wind particles at L1 point and return them to Earth
GRACE		ESSP	Earth Science	JPL	2002	Competed	6	Earth Gravity Measurement
Spitzer		Physics of the Cosmos	Astrophysics	JPL	2003	Directed	4	IR space telescope, the last of the Great Observatories
GALEX		Explorers	Astrophysics	JPL/CalTech	2003	Competed	1	UV space telescope
SWIFT		Explorers	Astrophysics	GSFC	2004	Competed	4	Gamma Ray burst detector
MESSENGER	X	Discovery	Planetary Science	APL	2004	Competed	7	Investigate Mercury
MRO	X	MEP	Planetary Science	JPL	2005	Directed	7	Investigate history of water on Mars
Deep Impact	X	Discovery	Planetary Science	JPL	2005	Competed	3	Comet impactor
Cloudsat		ESSP	Earth Science	JPL	2006	Competed	1	Radar observation of clouds
STEREO		STP	Heliospheric Science	GSFC/APL	2006	Directed	4	2 spacecraft looking at solar dynamics - Earth leading and trailing orbits
CALIPSO		ESSP	Earth Science	LARC	2006	Competed	3	Aerosols
New Horizons	X	New Frontiers	Planetary Science	APL	2006	Competed	7	Investigate Pluto
DAWN	X	Discovery	Planetary Science	JPL	2007	Competed	2	Investigate Ceres and Vesta protoplanets
AIM		Explorers	Heliospheric Science	LASP	2007	Competed	3	Aeronomy of Ice in Mesosphere
Fermi (GLAST)		Physics of the Cosmos	Astrophysics	GSFC	2008	Directed	2	Gamma Ray Telescope
IBEX		Explorers	Heliospheric Science	GSFC	2008	Competed	2	Interaction between solar wind and interstellar medium
Kepler		Discovery	Astrophysics	JPL	2009	Competed	1	Search for Earth-sized exoplanets
LRO	X	Robotic Lunar	ESMD/Planetary Science	GSFC	2009	Directed	7	Origin of the Moon
OCO		ESSP	Earth Science	JPL	2009	Competed	1	Carbon Dioxide Investigation. Mission failed due to launch vehicle failure

Composition of Average Life Cycle Cost & Cost Growth

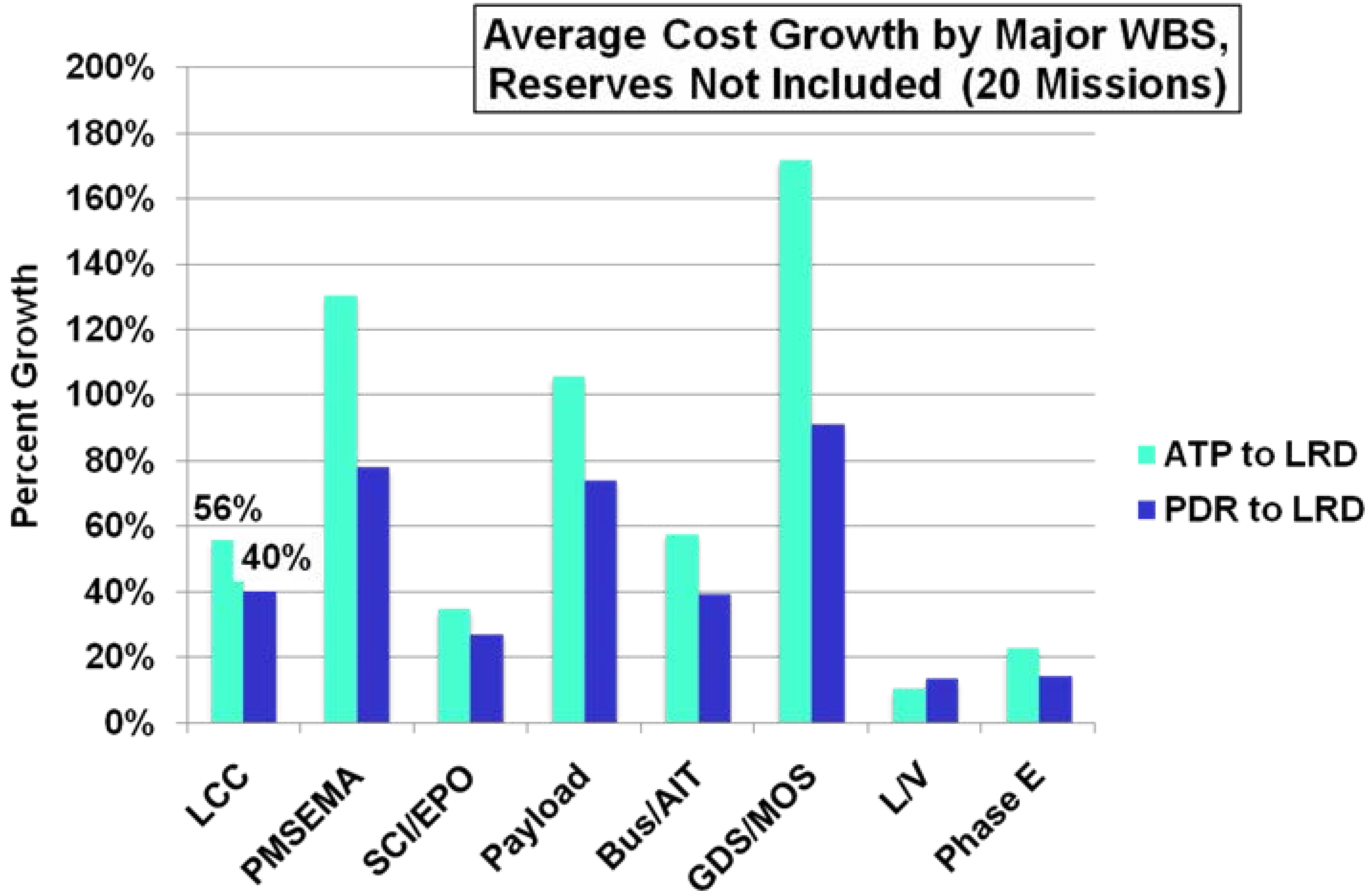
Category as Percent of Average LCC at Launch



Distribution of Growth of LCC From PDR to Launch



"Portfolio" % Average LCC Cost Growth

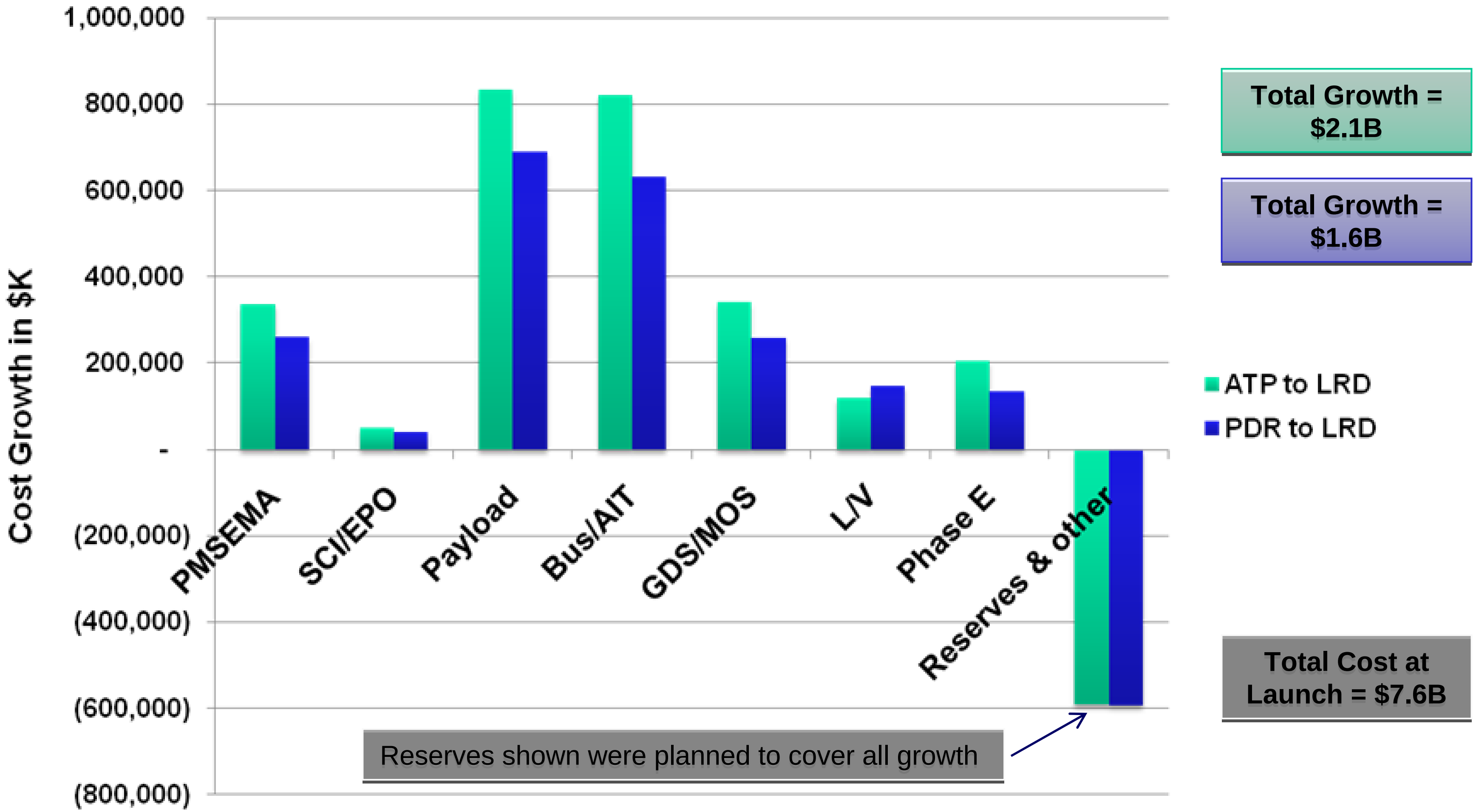


Largest Percent Growth for PMSEMA & GDS/OS

Growth = (Total LCC at Launch/Total LCC at KDP) -1
Note: ATP is equivalent to KDP-B

Total Cost Growth ($) by Major WBS Element

(20 Missions)



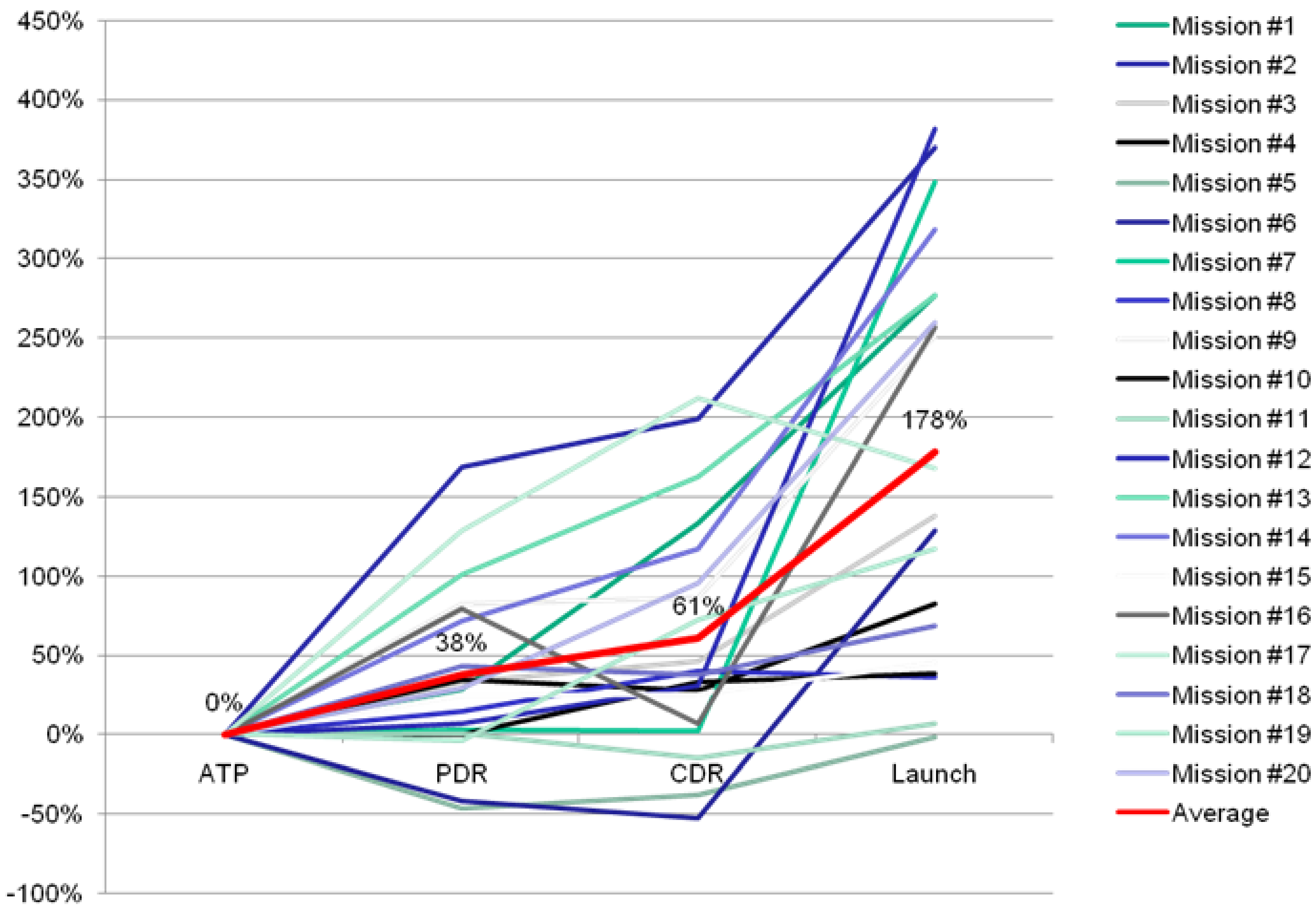
Largest Absolute Dollar Growth for Payload & Spacecraft

PM/SE/MA Growth

- Project Management/Systems Engineering/Missions Assurance Element typically seen as "Level of Effort" task
- Percent growth shown in following charts, however, implies that growth in PM/SE/MA is also due to underscoping initial effort
  - Average schedule growth of mission set is 38%* such that a level of effort task should grow by 38% as well
  - PM/SE/MA growth from Phase B start to launch is 178%
  - PM/SE/MA growth from PDR to launch is 114%
- Substantial growth in PM/SE/MA implies that initial team is understaffed or that PM/SE/MA account is "paying for" additional issues discovered with the spacecraft or instrument

* Note: As shown in "Optimism in Early Conceptual Designs and Its Effect on Cost and Schedule Growth: An Update", Bitten R., Freaner C., Emmons D., 2010 NASA Program Management Challenge, Galveston, Texas, February 9-10, 2010

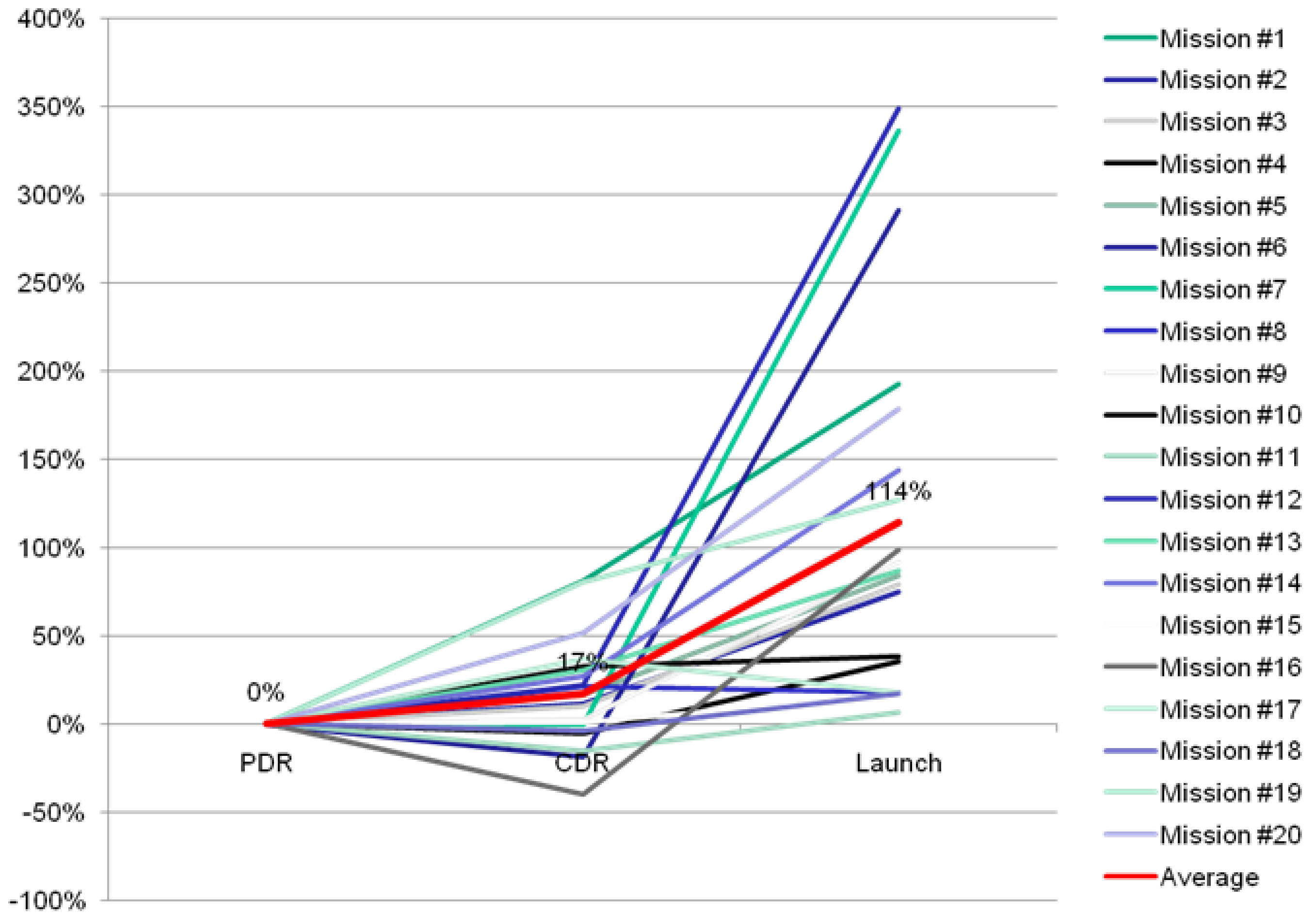
PMSEMA Cost Growth from ATP* (Phase B start)



Majority of PMSEMA Growth is Realized After CDR

* Note: Reserves not included

PMSEMA Cost Growth from PDR*



Majority of PMSEMA Growth is Realized After CDR

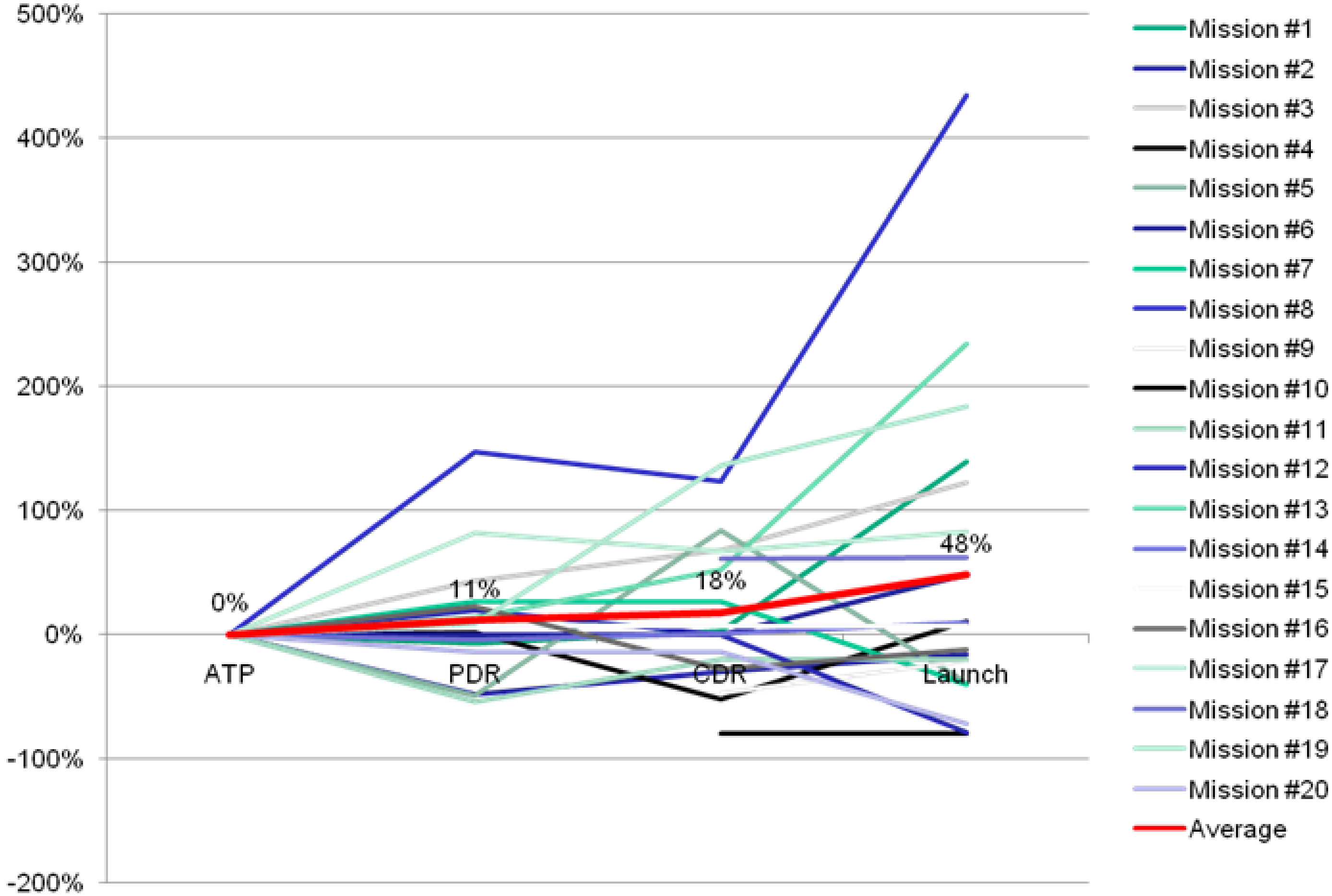
* Note: Reserves not included

Science/EPO Growth

- Science & Education and Public Outreach is also typically seen as "Level of Effort" task
- Percent growth shown in following charts shows that growth in Science/EPO is more consistent with level of effort tasking
  - Level of effort tasking should grow similar to the average schedule growth of the mission set of 38%*
  - Science/EPO growth from Phase B start to launch is 48%
  - Science/EPO growth from PDR to launch is 32%
- Data implies that scientist are getting it right in terms of estimating their staffing and sticking to it!

* Note: As shown in "Optimism in Early Conceptual Designs and Its Effect on Cost and Schedule Growth: An Update", Bitten R., Freaner C., Emmons D., 2010 NASA Program Management Challenge, Galveston, Texas, February 9-10, 2010

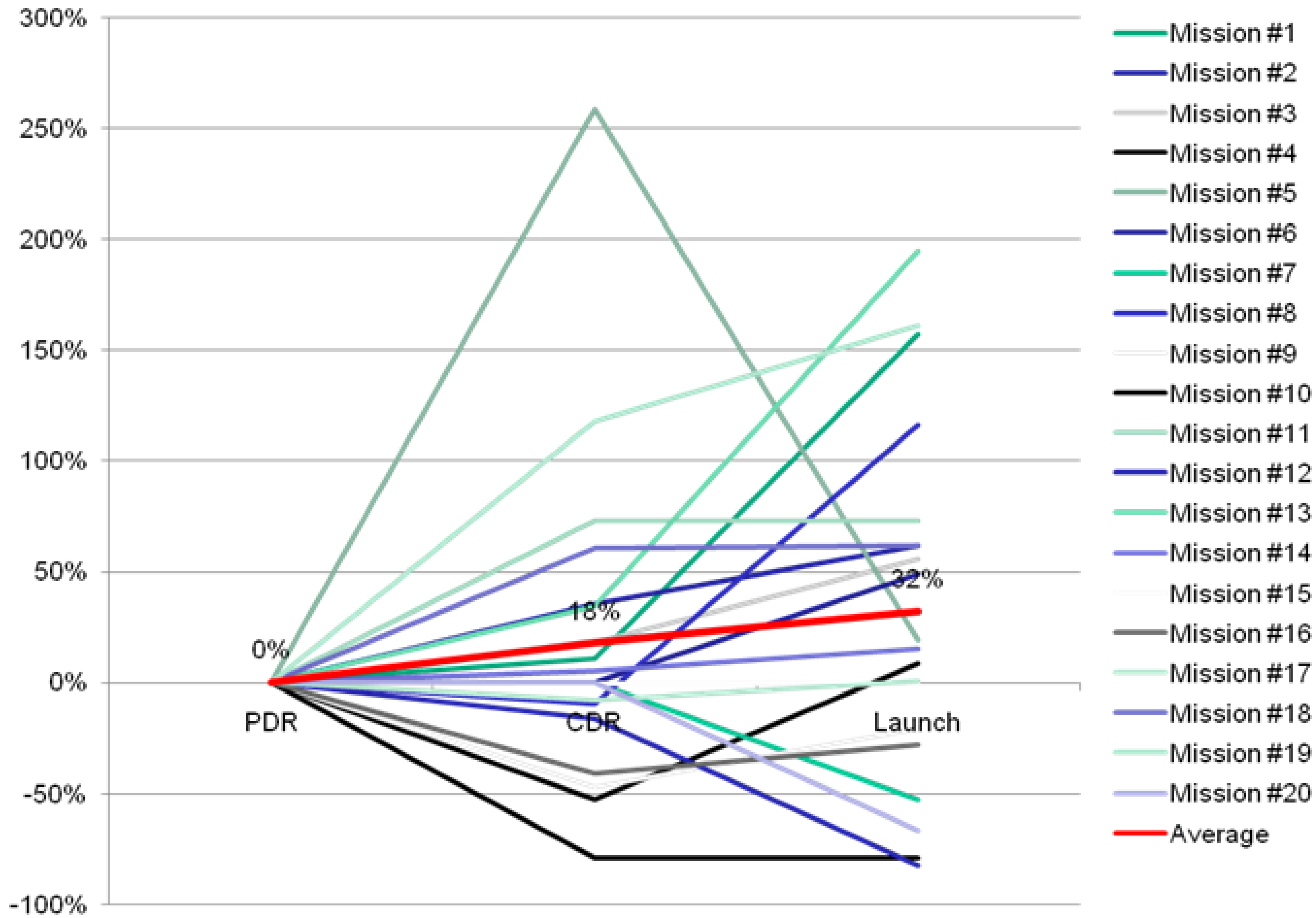
Science/EPO Cost Growth from ATP* (Phase B start)



Majority of Science/EPO Growth Occurs After CDR As Schedule Stretches

* Note: Reserves not included

Science/EPO Cost Growth from PDR*



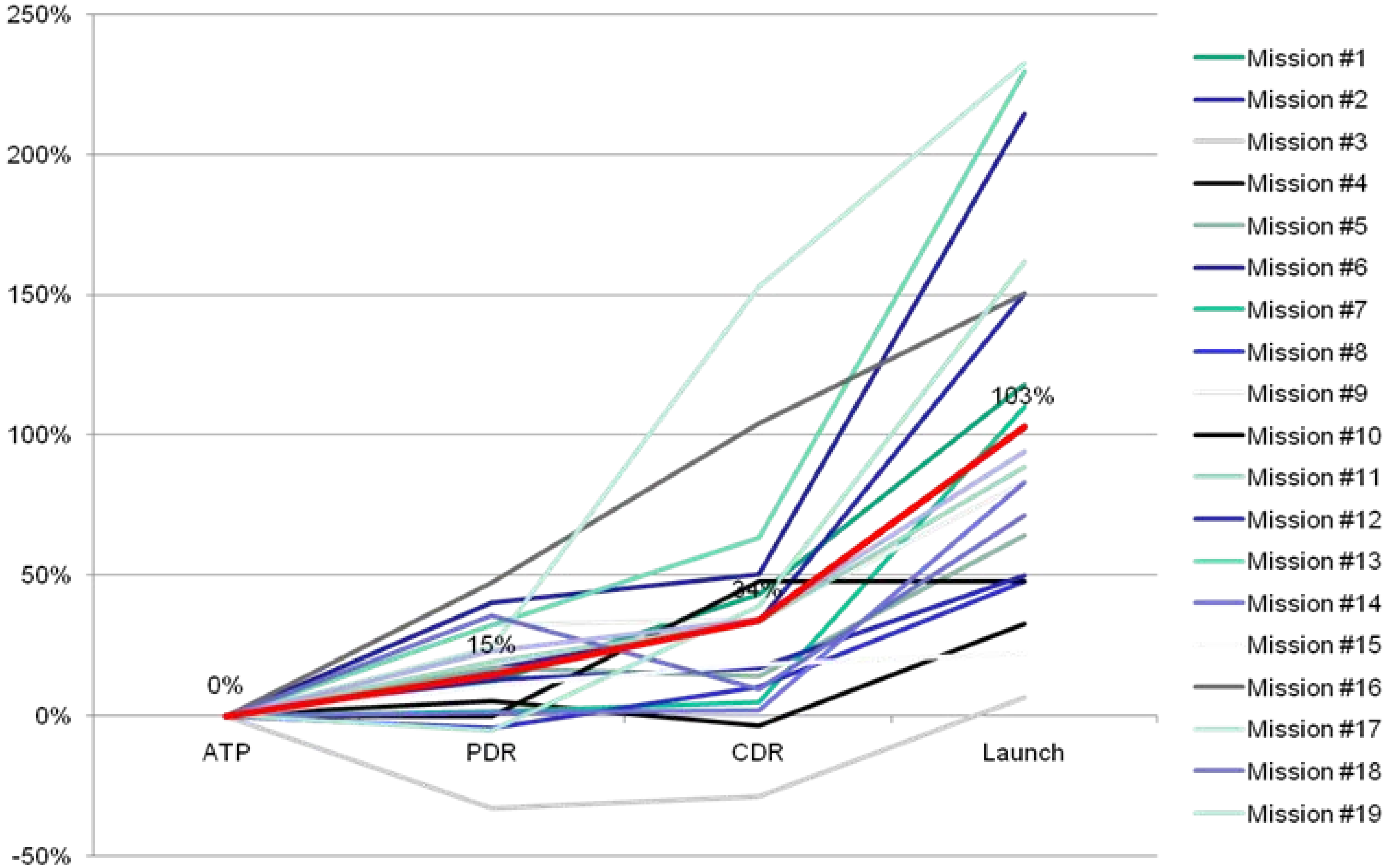
Science/EPO Grows Steadily After PDR

* Note: Reserves not included

Instrument Payload Growth

- Scientific instrument payloads for NASA missions are the primary development item
  - Typically, NASA instruments are pushing the state of the art for each successive mission as more data/better resolution/more capability is desired
- Instrument payload growth is the largest, in terms of absolute dollars, for any specific element
- Percent growth shown in following charts shows that growth in Payload is significant from both the start of Phase B and from PDR
  - Payload growth from Phase B start to launch is 103%
  - Payload growth from PDR to launch is 77%
- Data indicates that payload is still very immature at PDR

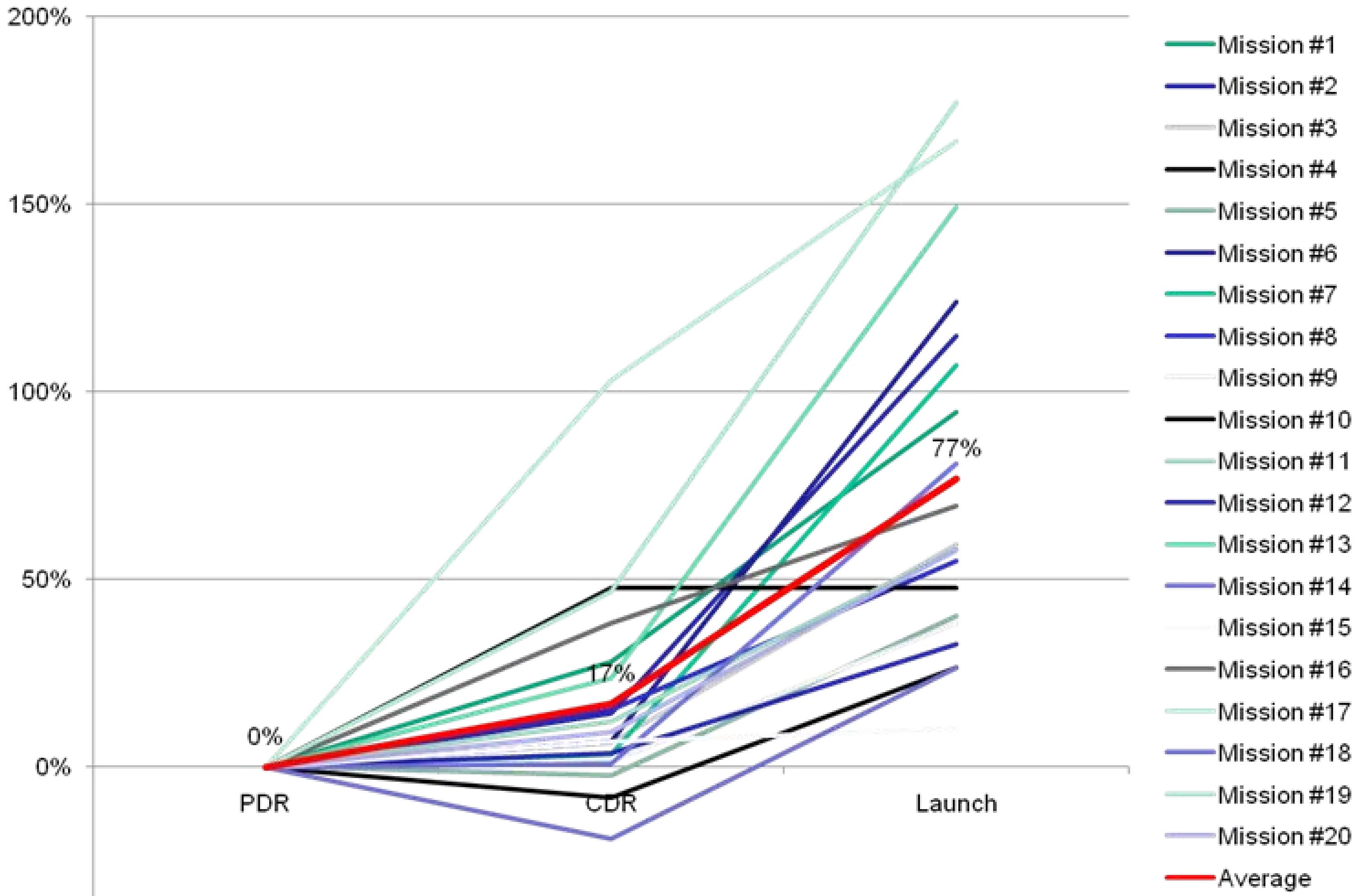
Payload Cost Growth from ATP* (Phase B start)



Majority of Payload Growth is Realized After CDR

* Note: Reserves not included

Payload Cost Growth from PDR*



Majority of Payload Growth is Realized After CDR

* Note: Reserves not included

Spacecraft Bus/Assembly, Integration & Test Growth

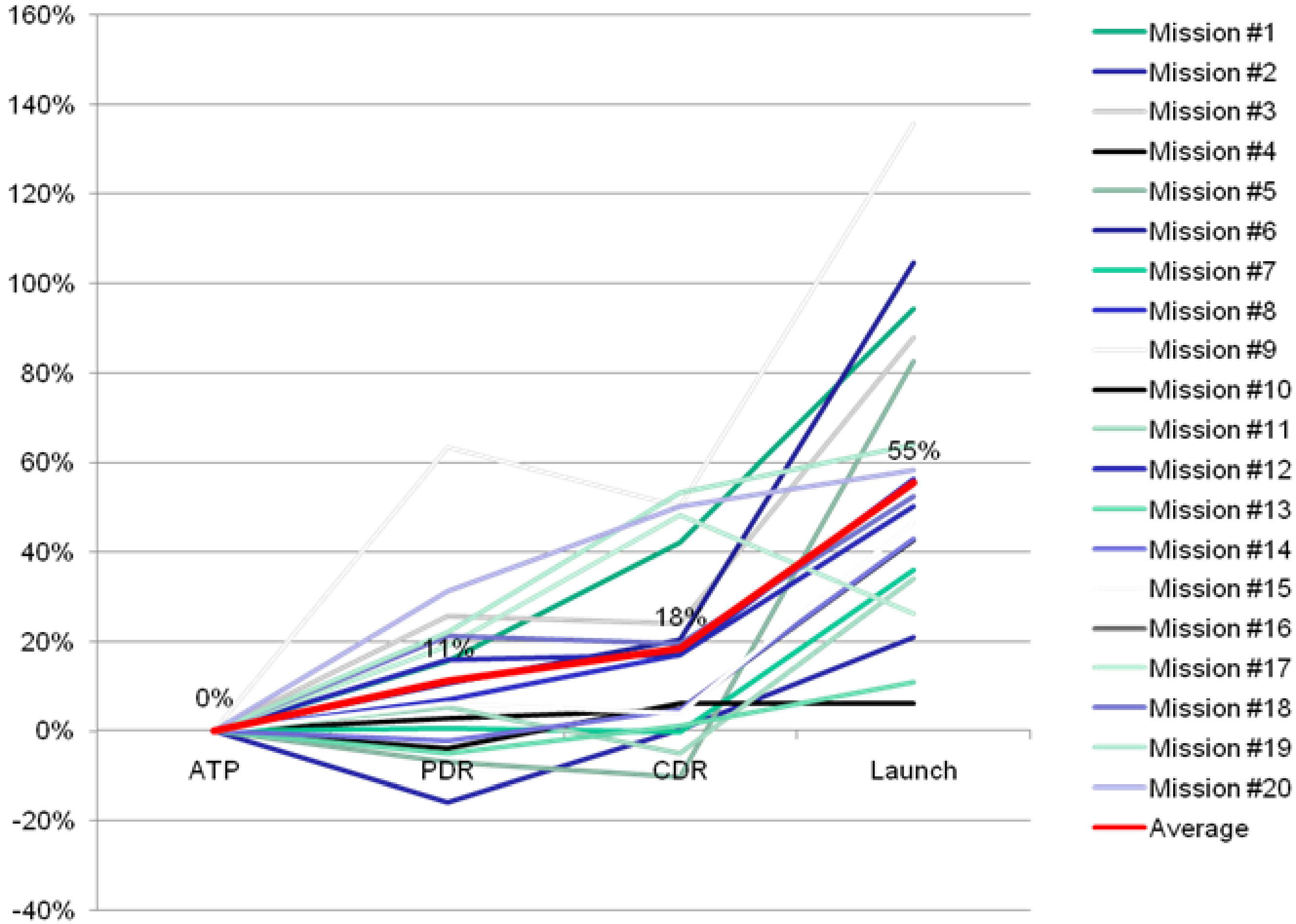
- Spacecraft for NASA missions, although still challenging, have less growth than scientific instrument payloads
  - Natural maturing of spacecraft and spacecraft component industry has made many capable spacecraft more readily available

- Percent growth shown in following charts shows that Bus/AIT still experience significant growth
  - Bus/AIT growth from Phase B start to launch is 55%
  - Bus/AIT growth from PDR to launch is 40%

- In many cases, however, the cost growth in the Bus/AIT growth is due to late instrument deliveries*

* Note: As shown in "Using Historical NASA Cost and Schedule Growth to Set Future Program and Project Reserve Guidelines", Bitten R., Emmons D., Freaner C., IEEE Aerospace Conference, Big Sky, Montana, March 3-10, 2007

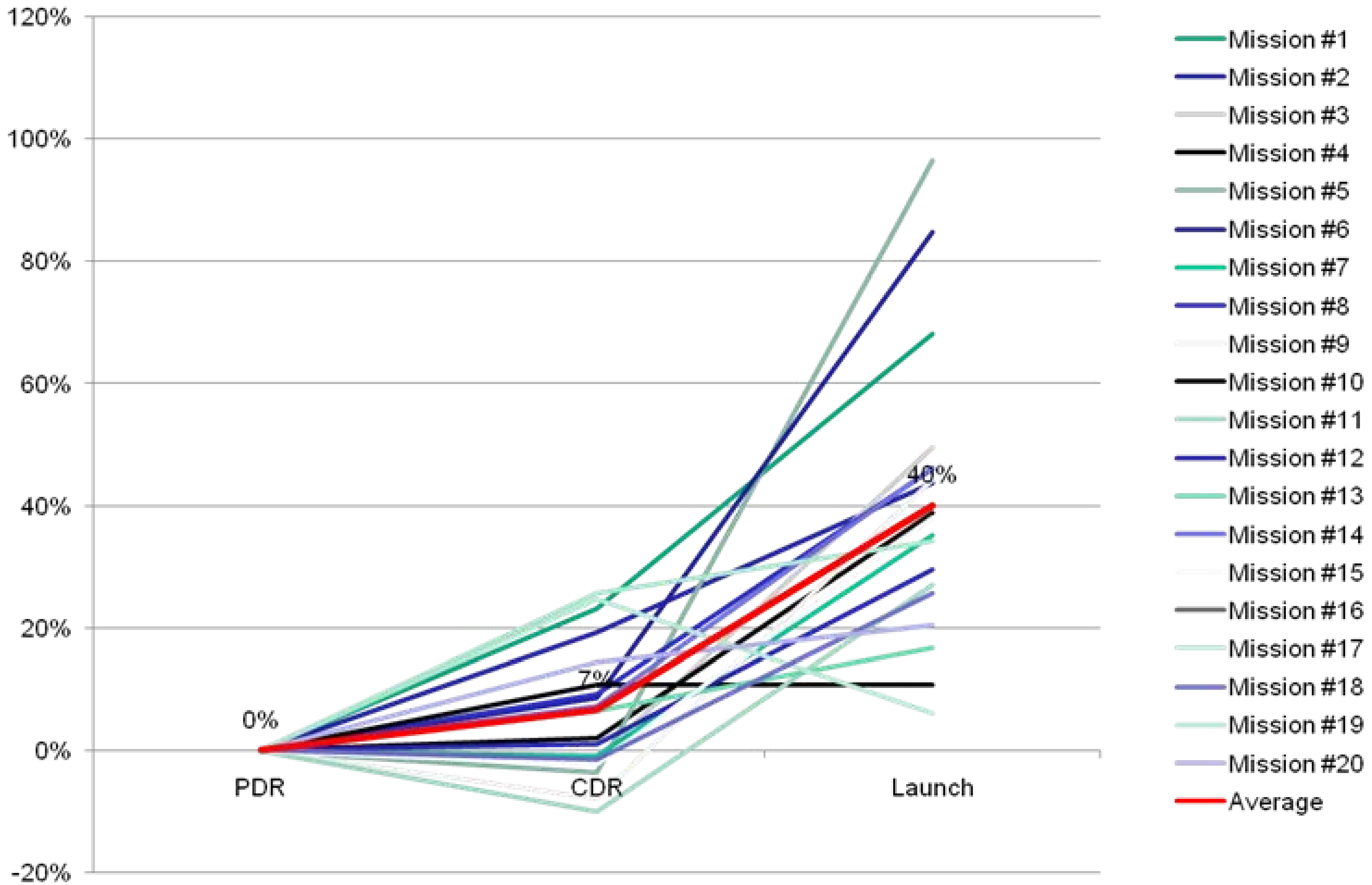
Bus/AIT Cost Growth from ATP*



Majority of Bus/AIT Growth is Realized After CDR

* Note: Reserves not included

Bus/AIT Cost Growth from PDR*



Majority of Bus/AIT Growth is Realized After CDR

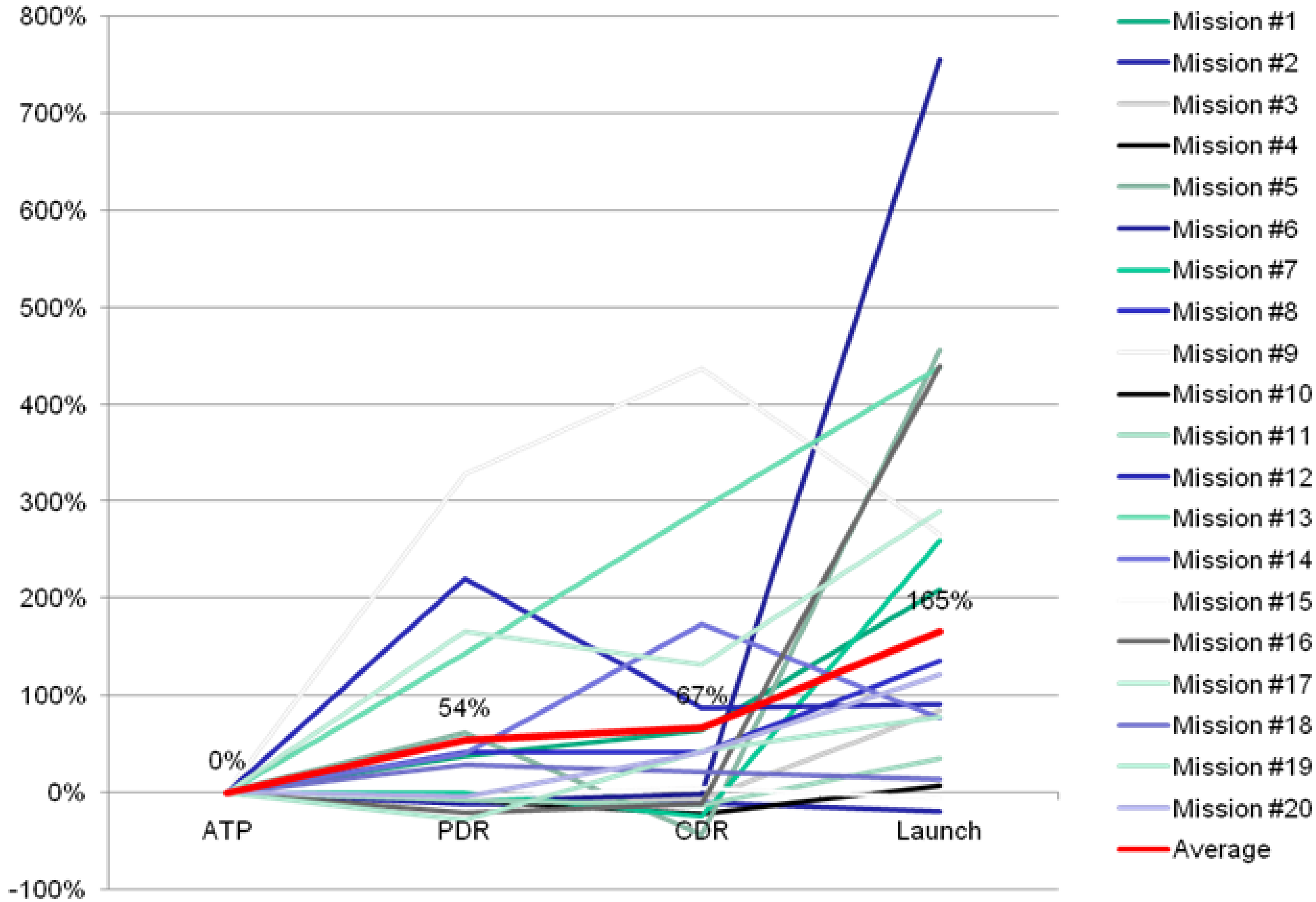
* Note: Reserves not included

Pre-Launch Ground Data System/Mission Operations System (GDS/MOS) Growth

- Typically, GDS/MOS development is not considered as challenging as spacecraft and instrument development
  - Many new missions utilize existing capabilities when developing the next generation systems
- Percent growth shown in following charts indicates that there is substantial variability in the growth in the development of GDS/MOS systems
  - GDS/MOS growth from Phase B start to launch is 165%
  - GDS/MOS growth from PDR to launch is 74%
- Unclear if this is due to initially optimistic heritage assumptions (i.e. code, procedure or hardware re-use) vs. unforeseen difficulty in developing and/or implementing data analysis algorithms
  - Further study should be conducted to determine root cause for growth

Pre-Launch GDS/MOS Cost Growth from ATP* (Phase B start)

EO-1 Excluded from Average

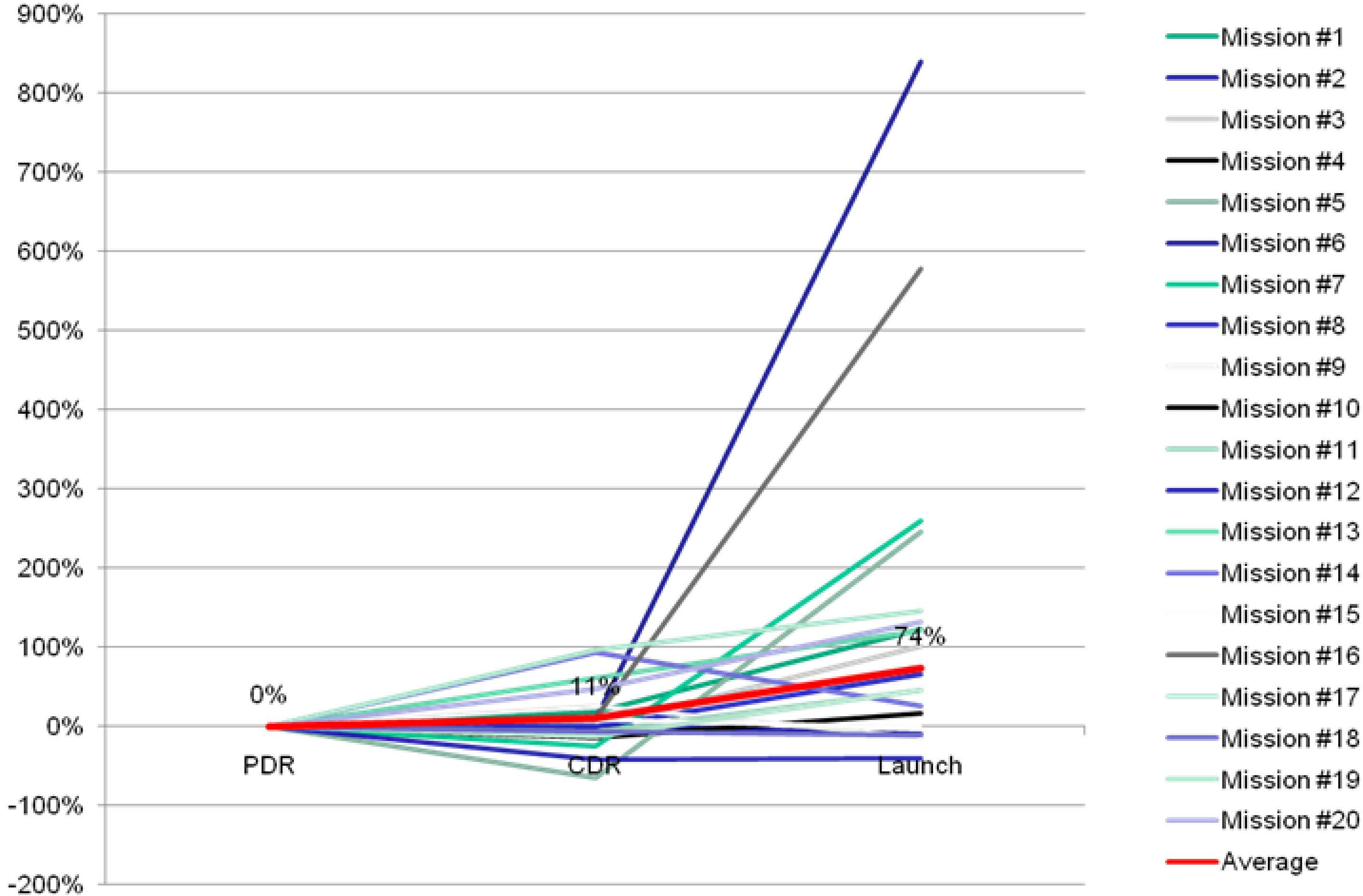


Majority of Pre-Launch GDS/MOS Growth is Realized After CDR

* Note: Reserves not included

Pre-Launch GDS/MOS Cost Growth from PDR*

EO-1 & CALIPSO Excluded from Average



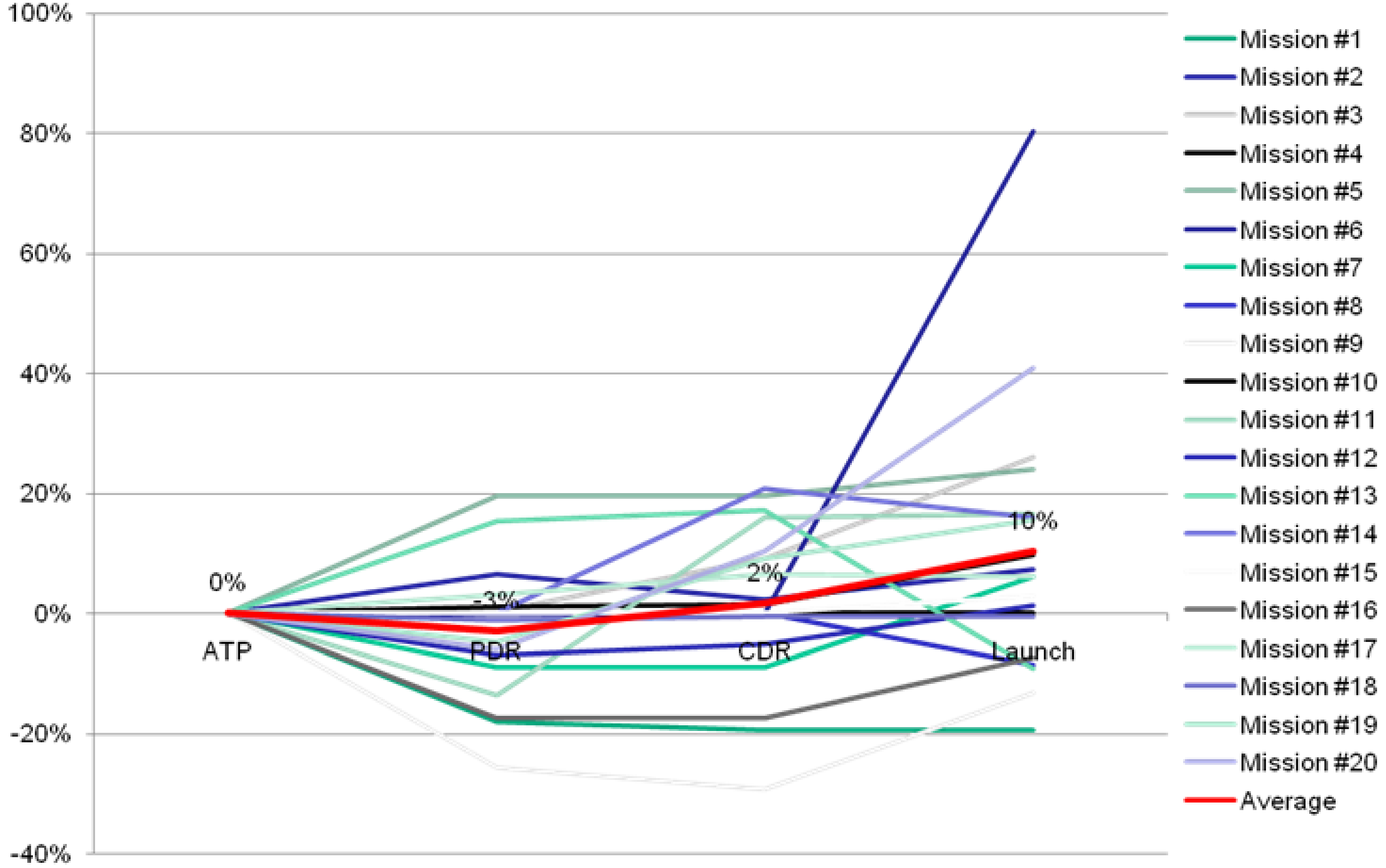
Majority of Pre-Launch GDS/MOS Growth is Realized After CDR

* Note: Reserves not included

Launch Vehicle Growth

- Launch Vehicle cost growth typically is identified as a major cost growth factor by NASA Project Managers
- Percent growth shown in following charts indicates that there is extremely little growth in Launch Vehicles
  - Launch vehicle growth from Phase B start to launch is only 10%
  - Launch vehicle growth from PDR to launch is only 14%
  - These values are much less than would be assumed due to schedule growth implying that launch vehicle contractors adjust their cost in an appropriate manner to account for schedule delays caused by the instrument and spacecraft providers
- With the retirement of Delta II and the use of Delta IV and Atlas V, launch vehicle cost growth for future missions could be significant as launch services contracts' cost increases to pay for low flight rate

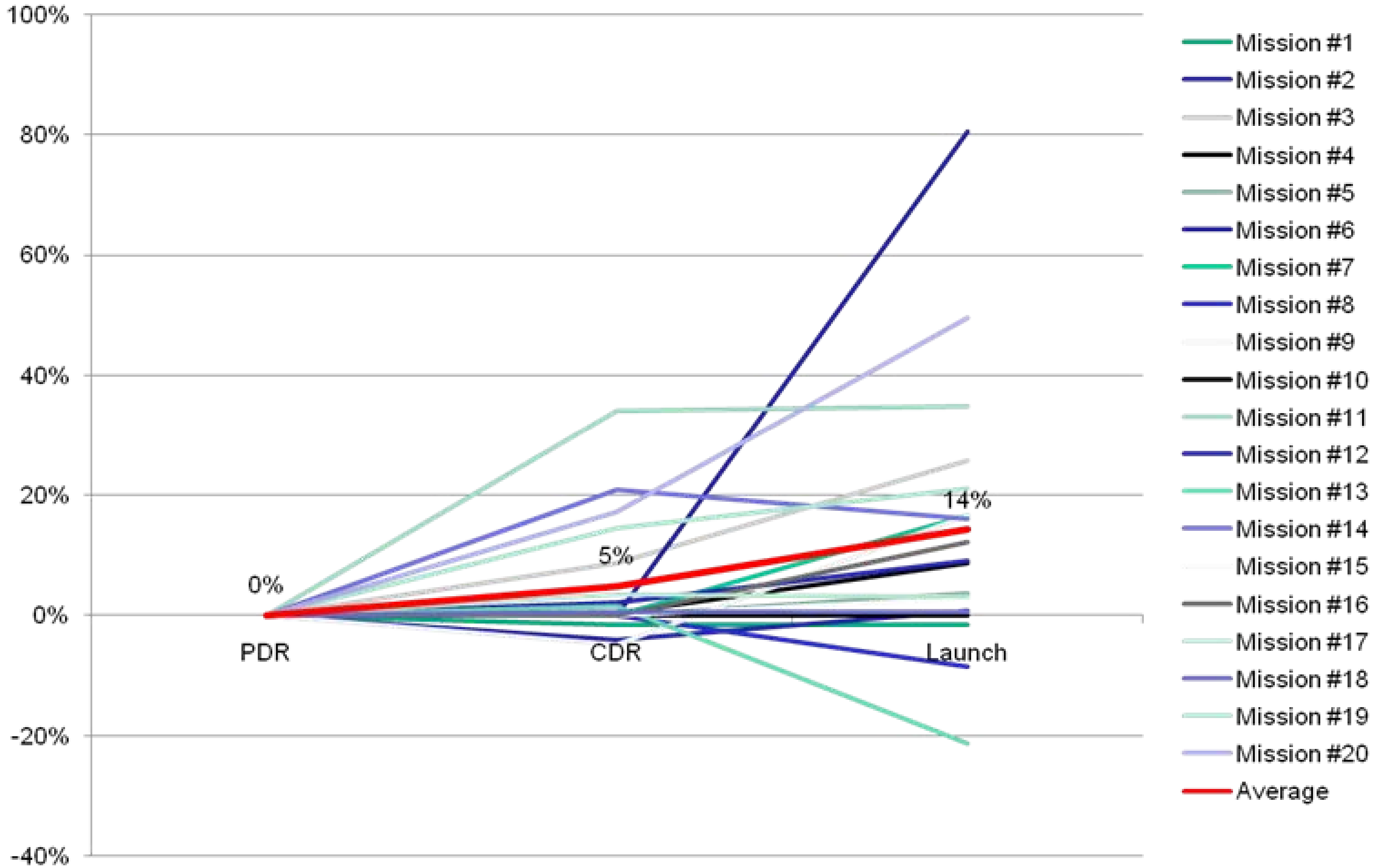
Launch Vehicle Cost Growth from ATP* (Phase B start)



Majority of Launch Vehicle Growth Occurs After CDR

* Note: Reserves not included

Launch Vehicle Cost Growth from PDR*



Majority of Launch Vehicle Growth Occurs After CDR

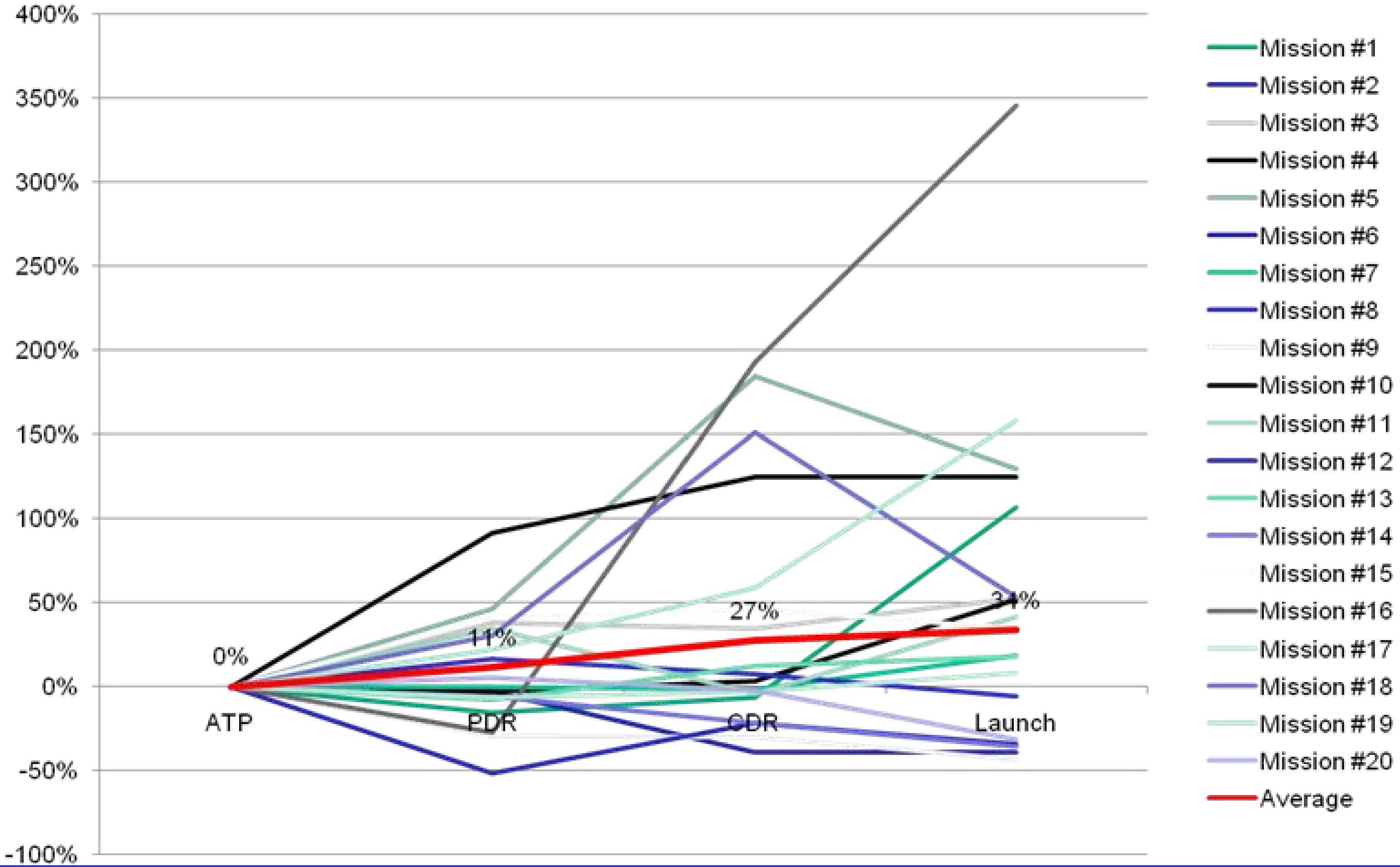
* Note: Reserves not included

Phase E Mission Operations Cost Growth

- Phase E cost growth can be problematic as increased Phase E cost takes funding away from the development of new missions
- Percent growth shown in following charts indicates that there is relatively little growth in Phase E for the missions studied
  - Phase E growth from Phase B start to launch is only 34%
  - Phase E growth from PDR to launch is only 21%
- There are two kinds of Phase E growth:
  - 1) The **Good** kind where total growth due to mission life being great than planned (as long as valuable data is being taken)
  - 2) The **Bad** kind where the annual Phase E cost is underestimated
- Further study is needed to find out what causes the “bad” kind

Planned Phase E Cost Growth from ATP* (Phase B start)

CALIPSO Excluded from Average

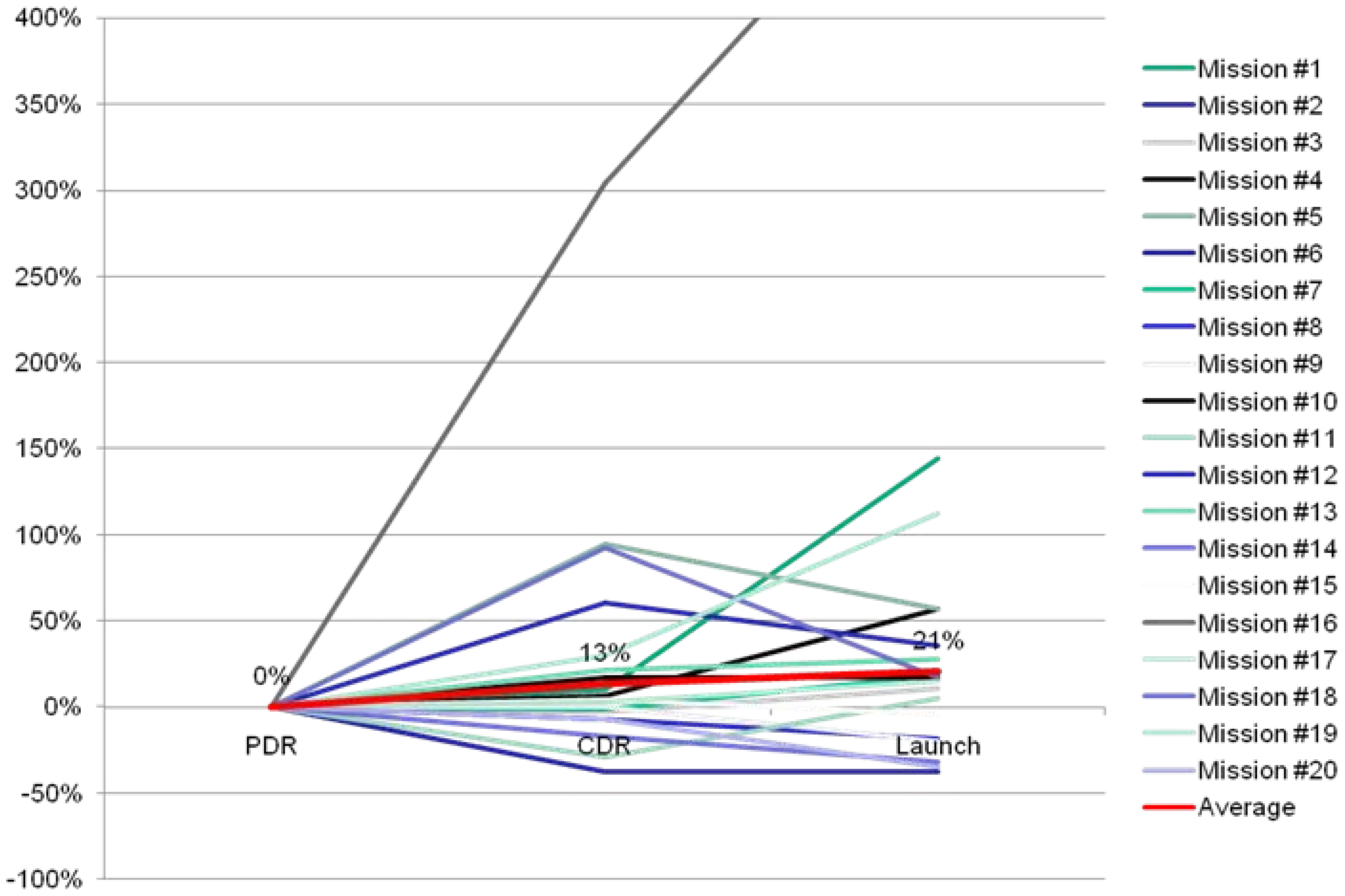


Majority of Phase E Growth Occurs Prior to CDR

* Note: Reserves not included

Planned Phase E Cost Growth from PDR*

CALIPSO Excluded from Average



Majority of Phase E Growth Occurs Prior to CDR

* Note: Reserves not included

Total Life Cycle Cost Growth

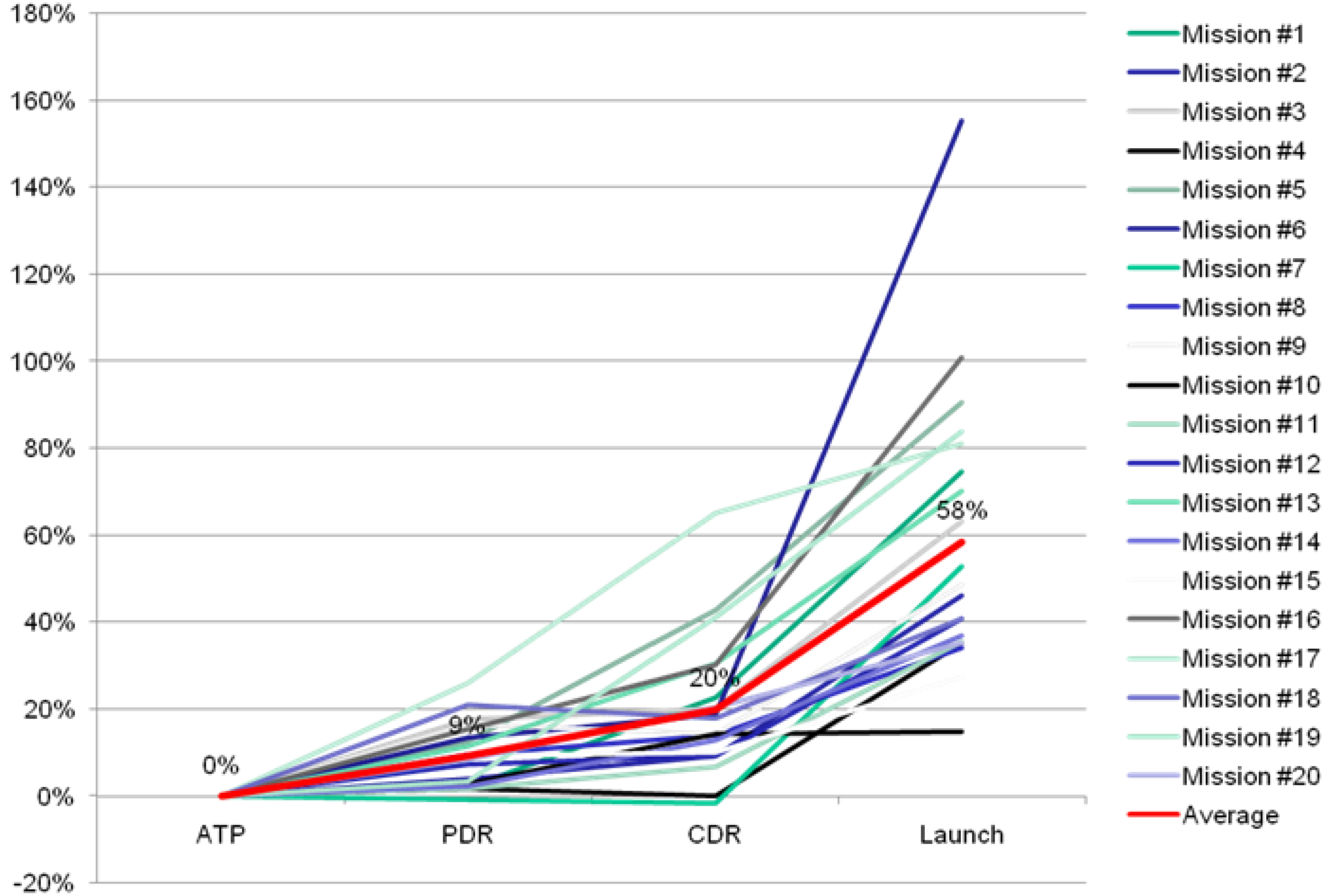
- Total life cycle cost growth is large with the primary contribution from the cost growth of the instrument development effort

- Additionally, the majority of growth occurs after PDR which implies that:
  - 1) Projects do not know cost and schedule will grow
  - 2) Projects ignore the indications that cost and schedule will grow
  - Neither of which are good options

- Percent growth shown in following charts indicates that there is relatively little growth in Phase E for the missions studied
  - LCC growth from Phase B start to launch is 58%
  - LCC growth from PDR to launch is only 45%

LCC Growth from ATP* (Phase B start)

(Includes Planned Phase E)



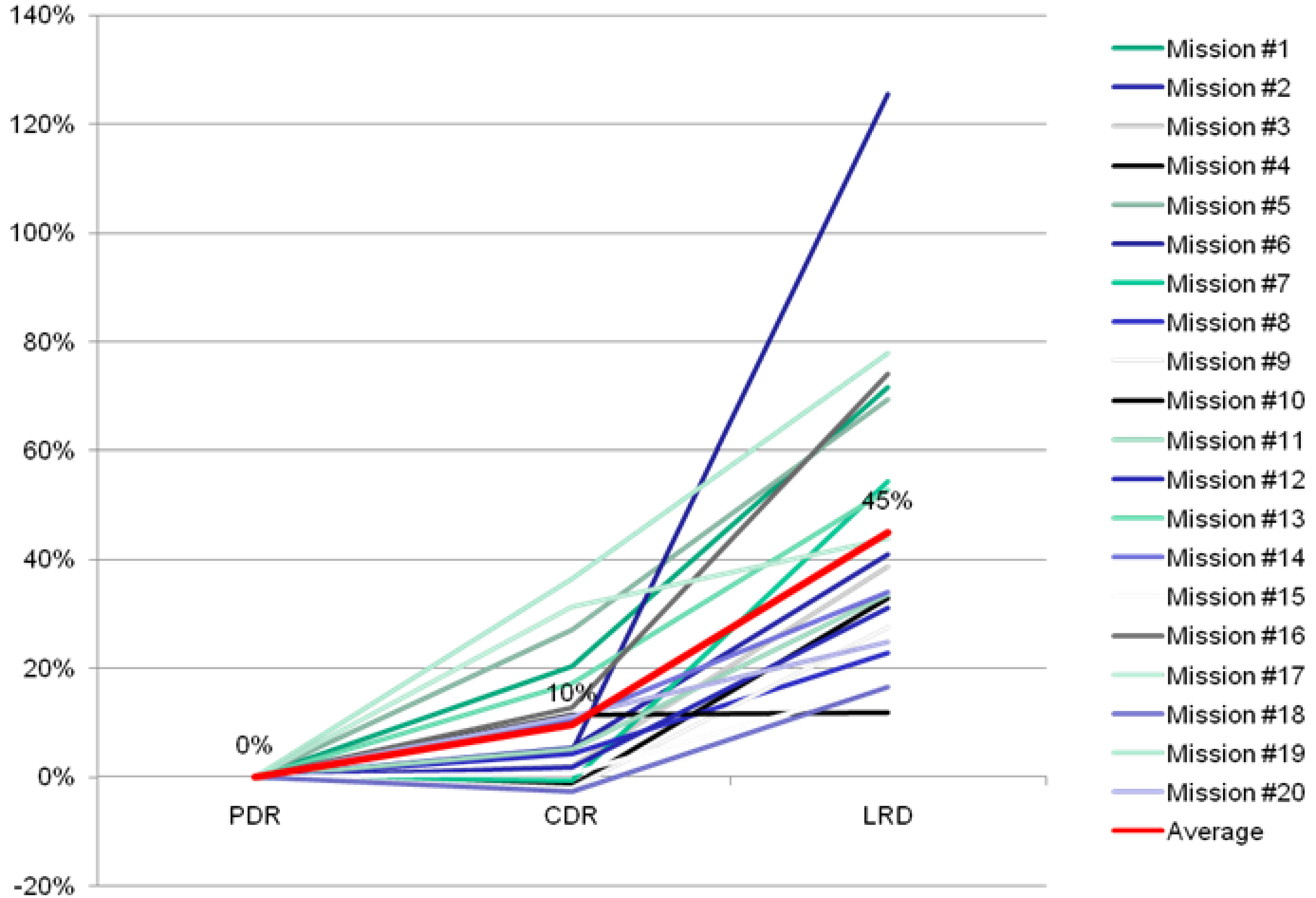
Majority of LCC Growth Occurs After CDR

* Note: Reserves not included

Growth = Average ((Mission LCC at Launch/Mission LCC at KDP)-1)

LCC Growth from PDR*

(Includes Planned Phase E)



Majority of LCC Growth Occurs After CDR

* Note: Reserves not included

Growth = Average ((Mission LCC at Launch/Mission LCC at KDP)-1)

Reserves Standards & The "Cost to Go" Fallacy

- JPL and GSFC guidelines on cost reserves rely on "cost to go", i.e. the current unencumbered reserves divided by remaining cost
- JPL Flight Project Practices, Rev. 7:
  - At PDR, budget reserves must be 25% of cost to go
  - At CDR, budget reserves must be 20% of cost to go
  - At start of ATLO, budget reserves must be 20% of cost to go
- GSFC "Gold Rules"
  - At PDR, budget reserves must be 25% of cost to go
- These reserves, however, are inadequate

• LCC growth from PDR to Launch averages 41% of *Total Cost* (reserves excluded), not cost to go
• LCC growth from CDR to Launch averages 32% of *Total Cost* (reserves excluded), not cost to go

The Probability that 25% Reserves at PDR Are Sufficient is Extremely Low

- Growth from PDR to Launch average is 41% (excluding EO-1)
  - Standard Deviation = 21%
  - Probability that a mission with 25% reserves at PDR will stay within those reserves by Launch = 22%
  - To achieve 70% CL, reserves of 47% would have been needed

- Growth from PDR to Launch average is 45% (including EO-1)
  - Standard Deviation = 28%
  - Probability that a mission with 25% reserves at PDR will stay within those reserves by Launch = 23%
  - To achieve 70% CL, reserves of 52% would have been needed

"Cost to Go" Percentage would need to be much Higher

So…Why Do We Have Cost Growth?

- Over-optimism at the start
  - Propensity for proposers to be in marketing mode
  - Initial Mass estimates are low
    - Average Payload Mass Growth PDR to Launch = 77%
  - Initial Schedule estimates are too short
  - Cost… Likely bid to the cost cap or available budget as opposed to what it realistically takes to develop the mission to meet mission requirements
- Cost estimators can provide more robust estimates by using wider ranges on parameters for estimating the input values used for cost risk analysis
  - Current Cost risk process appears to be underestimating the resource growth
- Schedule slips
  - Average Launch date slip from PDR plan: 13^{+} Months
  - Average Launch date slip from CDR plan: 10^{-} Months
  - Majority of schedule slips “occur” during ATLO but could have been anticipated earlier
- “Stuff” happens
  - Harder than we thought
  - Suppliers have problems
  - Things break
  - Congress/OMB/NASA HQ change funding profiles

What Can We Do to Decrease Cost Growth?

- Proper scoping of projects early in conceptual design to provide executable program plans
- Require better Basis of Estimate
  - Require proposers to show relevant actuals from prior missions at the subsystem level
  - “Relevant actuals” means Mass, Power, Cost, Schedule
  - Risk assessment and quantification of risk
- Independent validation of instrument resources, and the resulting spacecraft resources needed to meet mission requirements, would allow more accurate estimates
- Increase reserves is one possible solution
  - Reduces number of missions per year
  - Costs will likely rise to beyond the new reserves after a short time
- Incentivize contracts
  - Large rewards to Center/Team for performing to initial budget/schedule
  - Punishment
    - Easy to apply to Corporations: take away fee, cost share any overruns, etc.
    - Difficult to apply to NASA Centers