Johns Hopkins APPLIED PHYSICS LABORATORY

NASA Cost and Schedule Symposium

Math is Instrumental: An Analysis of Multi-Decade Space Flight Science Instrument Cost Performance

2024 NASA Cost & Schedule Symposium
Langley Research Center (LaRC)

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Jet Propulsion Laboratory
California Institute of Technology

Background

- Historically, one of the most significant contributors to cost growth of NASA's science missions has been instrument development cost growth
- There is a strong correlation between instrument cost growth and total mission cost growth where instrument cost growth influences mission cost growth at a 2-to-1 factor
- Cost growth at the instrument level tends to snowball up to the mission level by causing changes needed to the mission or spacecraft itself or by simply causing delays in the instrument integration, leading to "marching army" costs for the mission

Background

- Instruments support a wide range of scientific research which are used to advance all the major scientific disciplines of astrophysics, planetary science, heliophysics, and Earth Science
- Instruments can vary greatly in terms of design and complexity
- With so many paths to organize instruments across their functional design and scientific disciplines, grouping instruments into meaningful categories has been challenging

Aerospace's SSIT

- First released in 2017 and was updated to version 2.0 in 2020
- Commonly used for cost modeling for estimating costs of future instruments
- Several models use SSIT framework
- Three levels of categorization
- Remote-sensing focus for our research

1 Fields	1.1 Electric Field	
		1.1.1 Double Probe
		1.1.2 Electron Drift
	1.2 Magnetometer	
		1.2.1 Fluxgate
		1.2.2. Search Coil
		1.2.3 Ionized Gas Vapor
		1.2.4 Magnetoresistive
2 Particles	2.1 Mass Spectrometer	
		2.1.1 Quadrupole MS
		2.1.2 Time-of-Flight MS
		2.1.3 Sector Field MS
		2.1.4 Ion Cyclotron Resonance MS
	2.2 Charge and X-ray Detector	
		2.2.1 High Energy Particle Detector
		2.2.2 Low Energy Particle Detector
	2.3 Plasma Instrument	
		2.3.1 Plasma Probe
		2.3.2 Retarding Potential Analyzer
		2.3.3 Ion Drift Meter
	2.4 Dust Detector	
3 XRT		
4 Optical	4.1 Passive Optical	
		4.1.1 Cryo-Cooled Passive Optical
		4.1.2 Optical Telescope Assembly
		4.1.3 Radiometer
		4.1.4 Pyrheliometer
		4.1.5 Film Camera
		4.1.6 Interferometer
		4.1.7 Single-Band Imager
		4.1.8 Natural Color Imager
		4.1.9 Multi-Spectral Imager/Spectrometer
		4.1.10 Hyper-Spectral Imager/Spectrometer
	4.2 Active Optical	
		4.2.1 Laser Ranging
		4.2.2 Laser Velocimeter / Vibrometer
		4.2.3 Laser Imager
		4.2.4 Laser Scatterometer
5 MW/RF	5.1 Passive MW/RF	
	5.2 Active MW/RF	
		5.2.1 MW/RF Ranging
		5.2.2 MW/RF Imager
		5.2.3 MW/RF Scatterometer
6 Support	6.1 Scan Platform	
	6.2 Deployment Mechanism	
	6.3 Robotic Arm	
	6.4 Data Processing Unit	
	6.5 Cryogenic Systems	
		6.5.1 Cryogenic Radiator
		6.5.2 Expendable Cryogen Cooler
		6.5.3 Mechanical Cryocooler
	6.6 Accelerometer	
	6.7 Ultra Stable Oscillator	
	6.8 Mirror Target	
	6.9 Positioning Receivers	
7 Atmospheric & Surface	7.1 Entry and Descent Sensor	
	7.2 Meteorological Station	
	7.3 Sample Collector	
	7.4 Sample Analyzer	
	7.5 Seismographer	
8 Comm	8.1 MW/RF Communications	
	8.2 Laser Communications	
9 Other		

Source: Space Scientific Instrument Taxonomy (SSIT) V2.0.

Methodology & Assumptions

- Cost performance of 106 domestic remote-sensing science instruments
  - Launch dates from 2004 to 2023
  - Instruments from 48 science missions
- Cost data collected via PDR and Launch CADRes (Part C)
- Programmatic data collected via CADRes (Parts A, B)
- Costs were normalized to include Phases A-D
- Cost growth was calculated from PDR to Launch as:

$$cost\ growth = \frac{(Cost\ @\ Launch - Cost\ @\ PDR)}{Cost\ @\ PDR}\ x\ 100\%$$

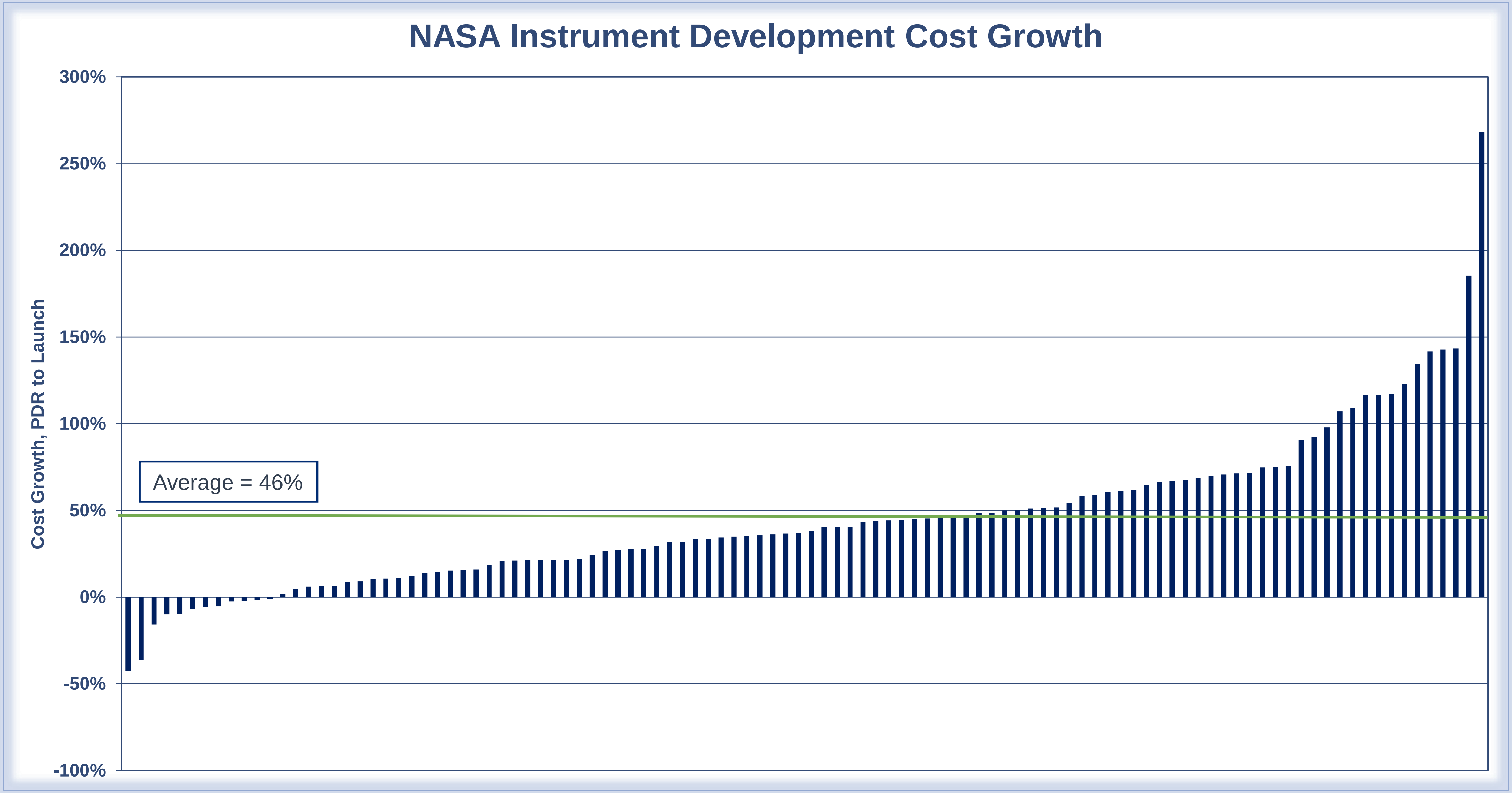
Methodology & Assumptions

- The cost of each instrument represents the effort needed to design, develop, and deliver the instrument to the spacecraft
  - For single instrument payloads, costs for payload PM/SE/MA were included with the assumption that these payload level costs pertain to the one single instrument
  - For multiple instrument payloads, costs for payload level PM/SE/MA under the payload WBS were excluded
  - For each instrument, instrument-level assembly and testing costs were included
- For dual spacecraft systems with multiple copies of instruments, costs were normalized to costs for the first unique unit
- For instruments that are a part of an instrument suite:
  - If there was detail provided at the instrument level, the unique instruments were included
  - If there was only detail provided at the suite level, the suite was included in the dataset

Methodology & Assumptions

- Instruments were excluded from the dataset if there was missing data
- De-scoped instruments were removed
- Foreign built instruments were removed
- Support instruments were excluded
  - Shared DPU costs were not allocated to remote-sensing science instruments that utilize a shared DPU
- Communications instruments were excluded

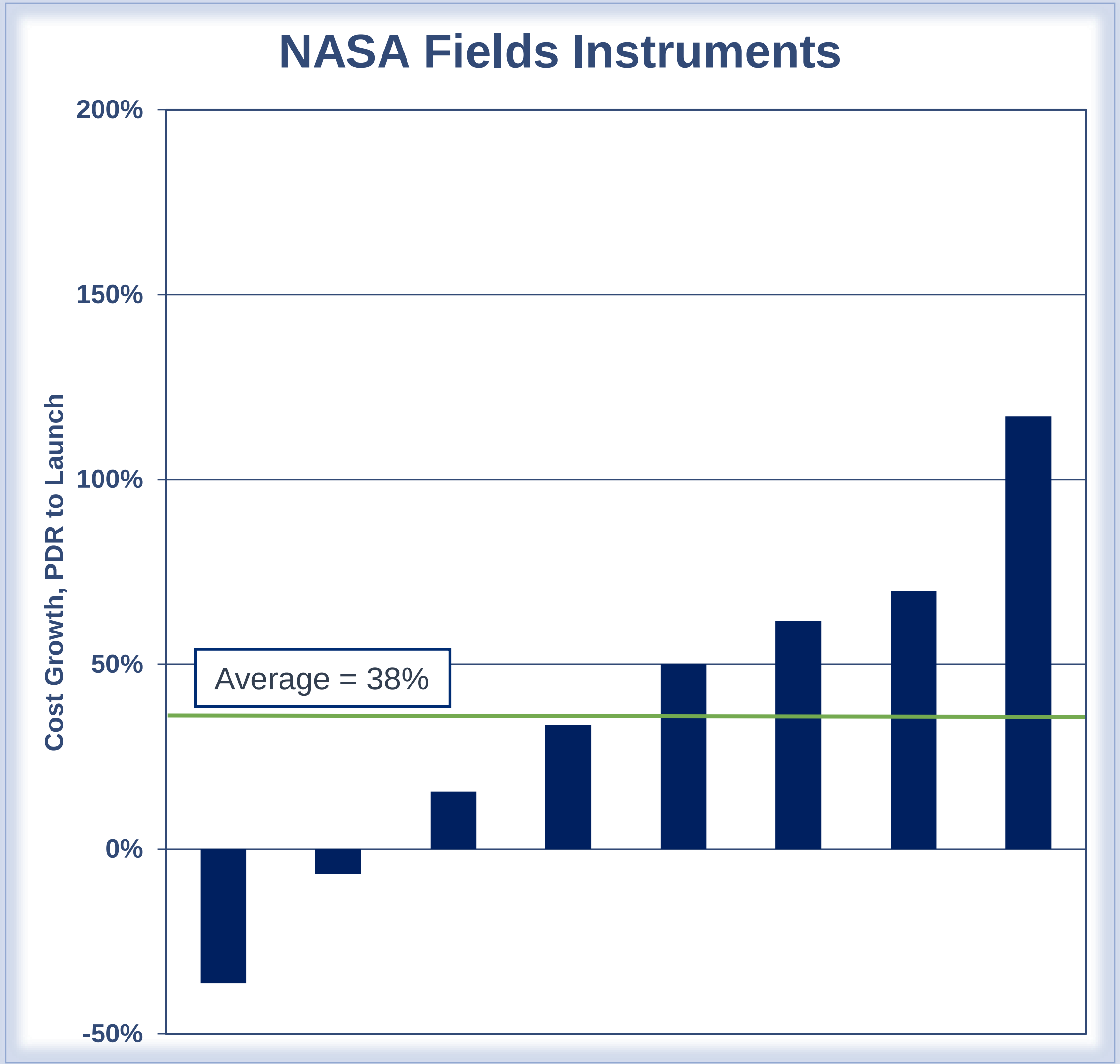
NASA Instrument Cost Growth

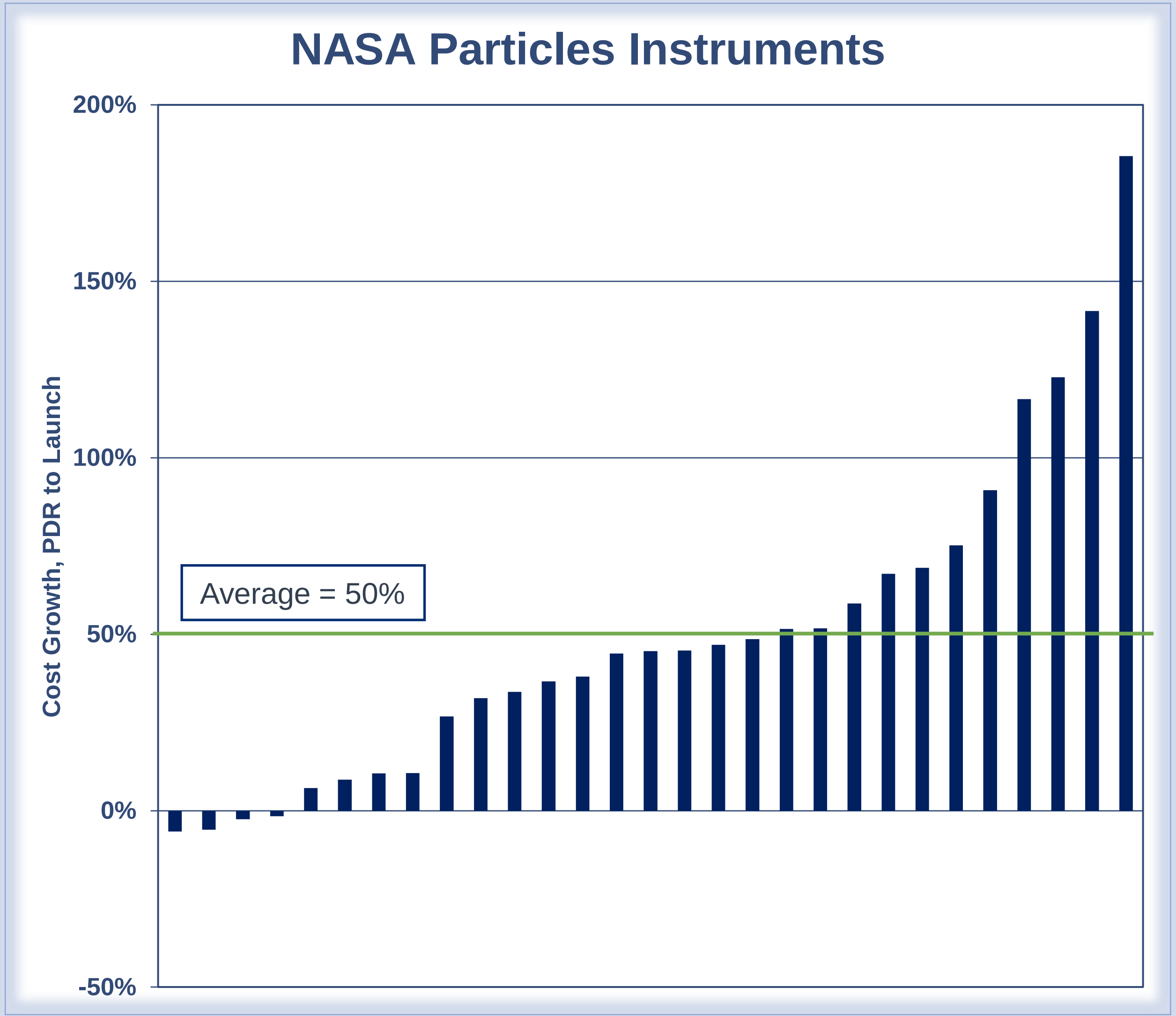


Potential Cost Growth Factors

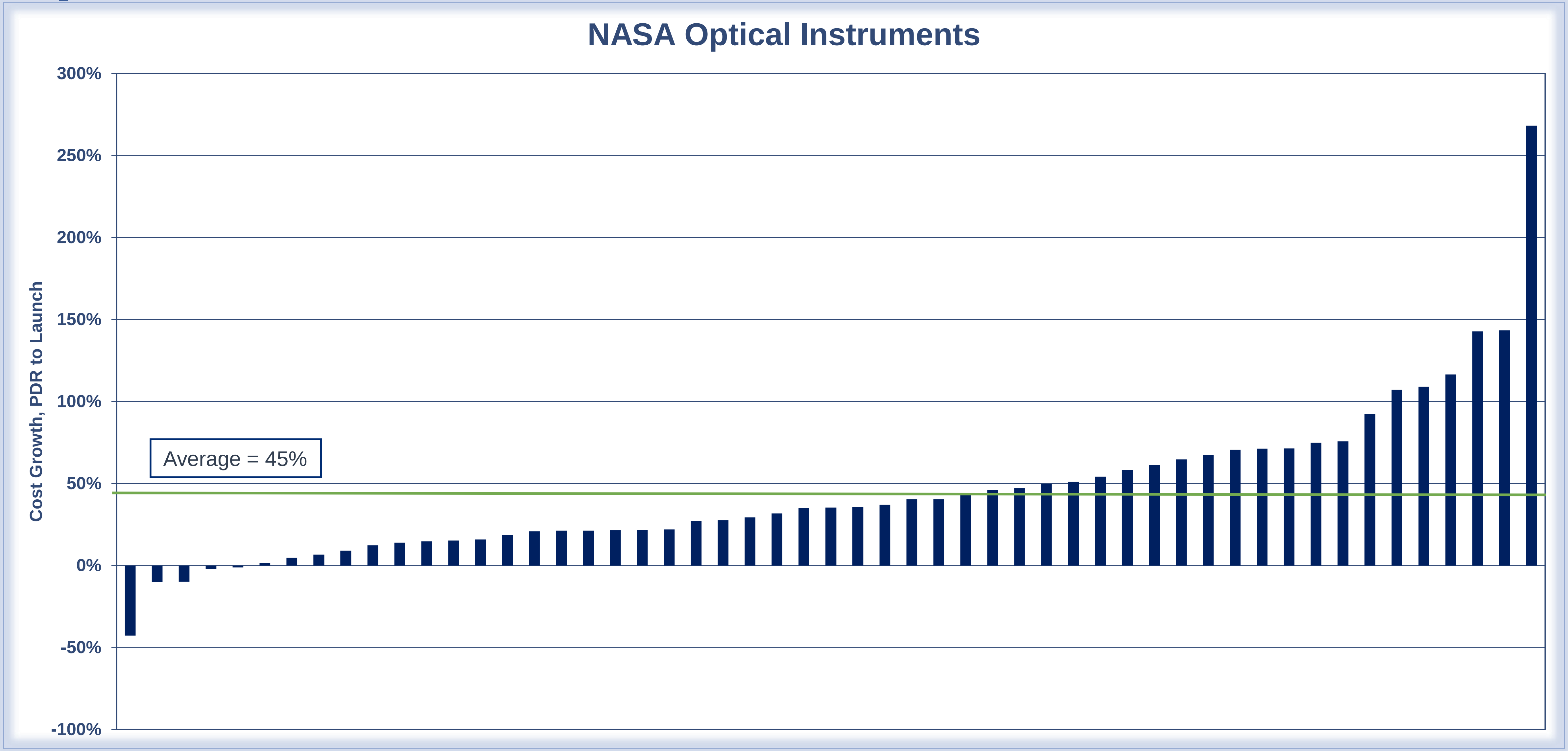
- Instrument Type (Level 1)
- Total Instrument Cost
- Instrument Mass
- Instrument Mass Growth
- Mission Acquisition Strategy
- Mission Class
- Destination
- Science Mission Directorate (SMD) Division
- Policy Era

Fields and Particles Instruments

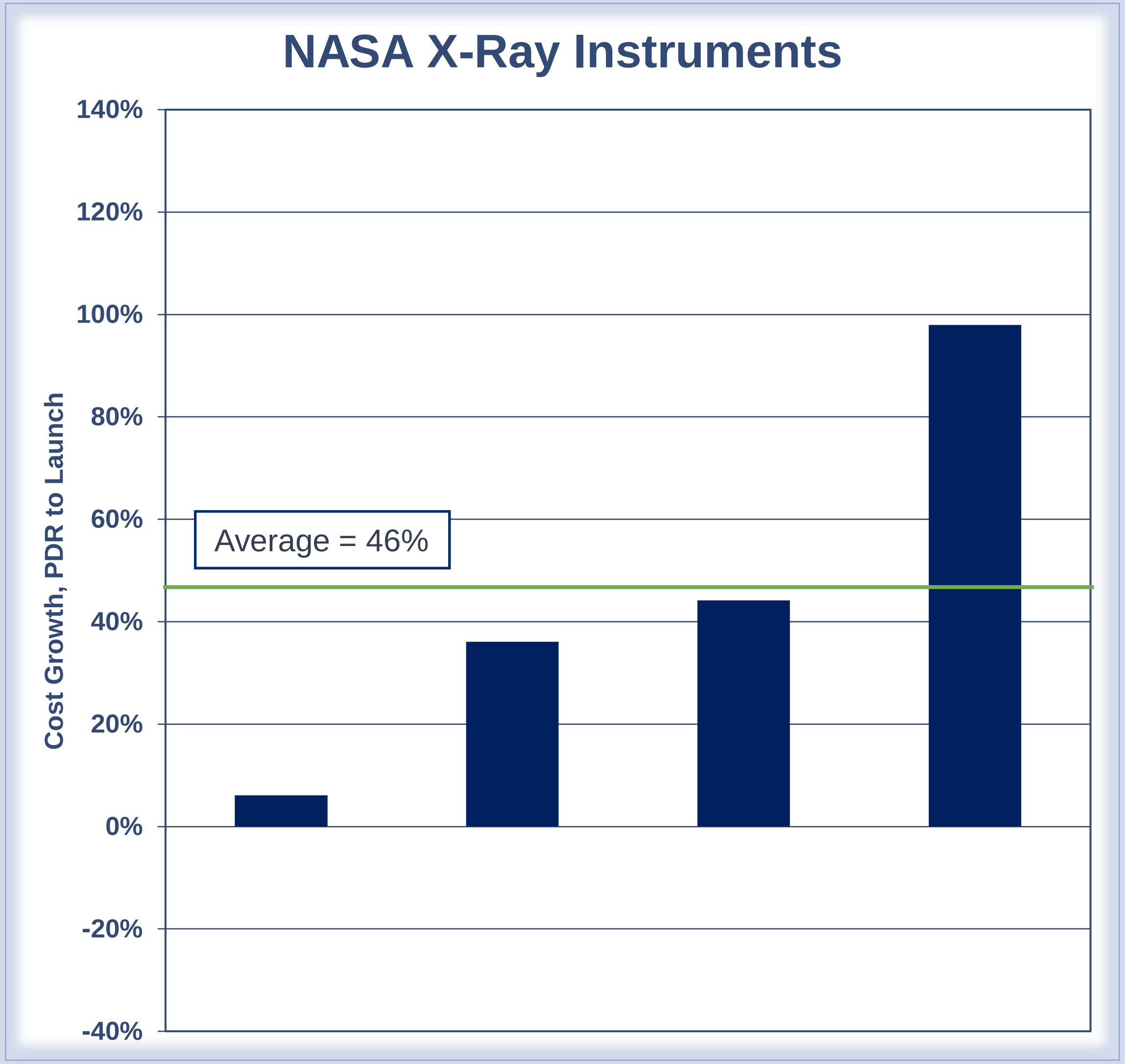


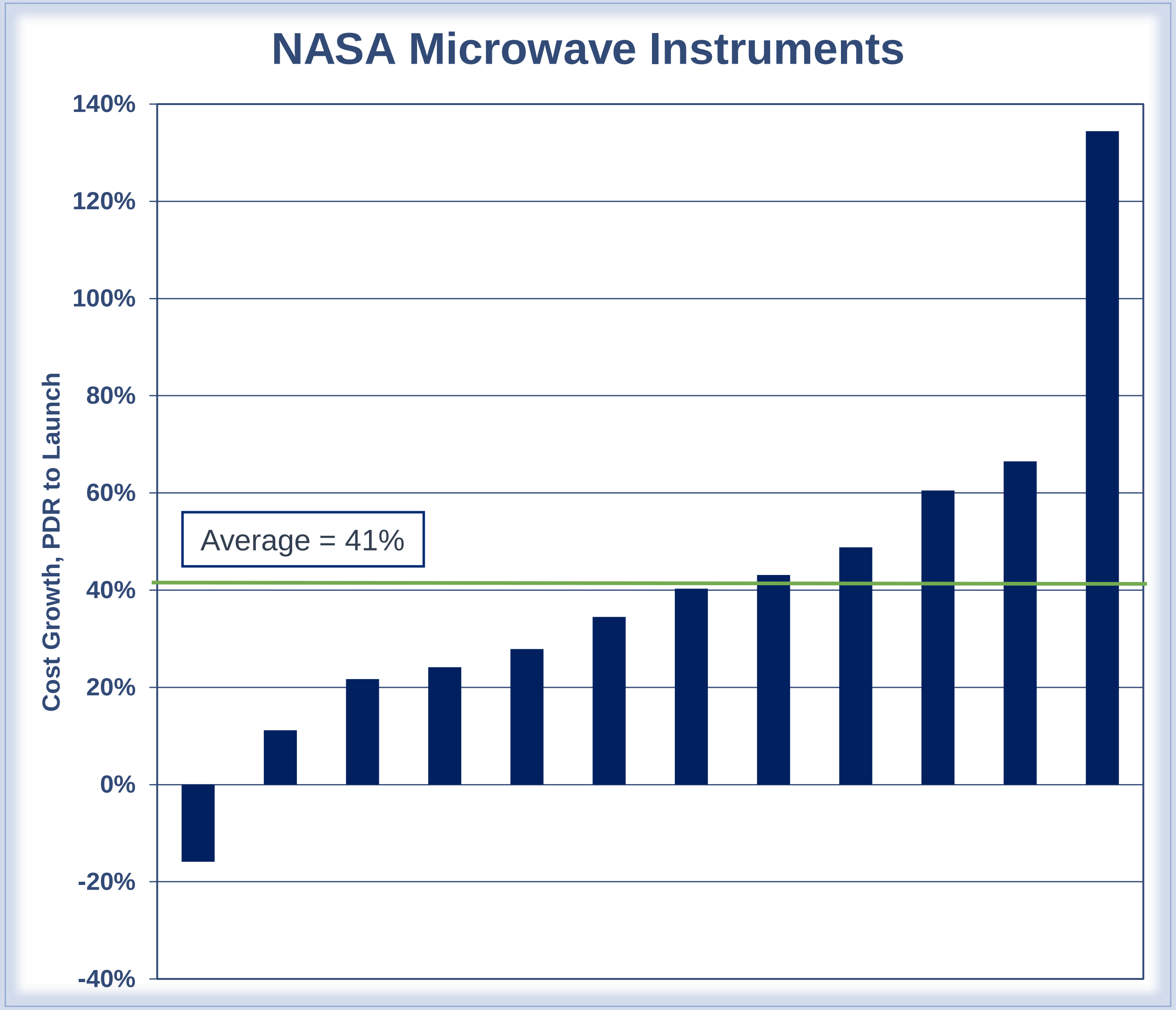


Optical Instruments



X-Ray and MW/RF Instruments





Cost Growth (%) by Instrument Type (Level 1)

Instrument Type	Average Cost Growth
Fields Instruments	38%
Particles Instruments	50%
X-Ray Instruments	46%
Optical Instruments	45%
MW/RF Instruments	41%

- $H_0: \mu_{fields} = \mu_{particles} = \mu_{x-ray} = \mu_{optical} = \mu_{MW/RF}$
- $H_1: means\ are\ not\ all\ equal$

F Test Summary	
F statistic	0.14
P value	0.97

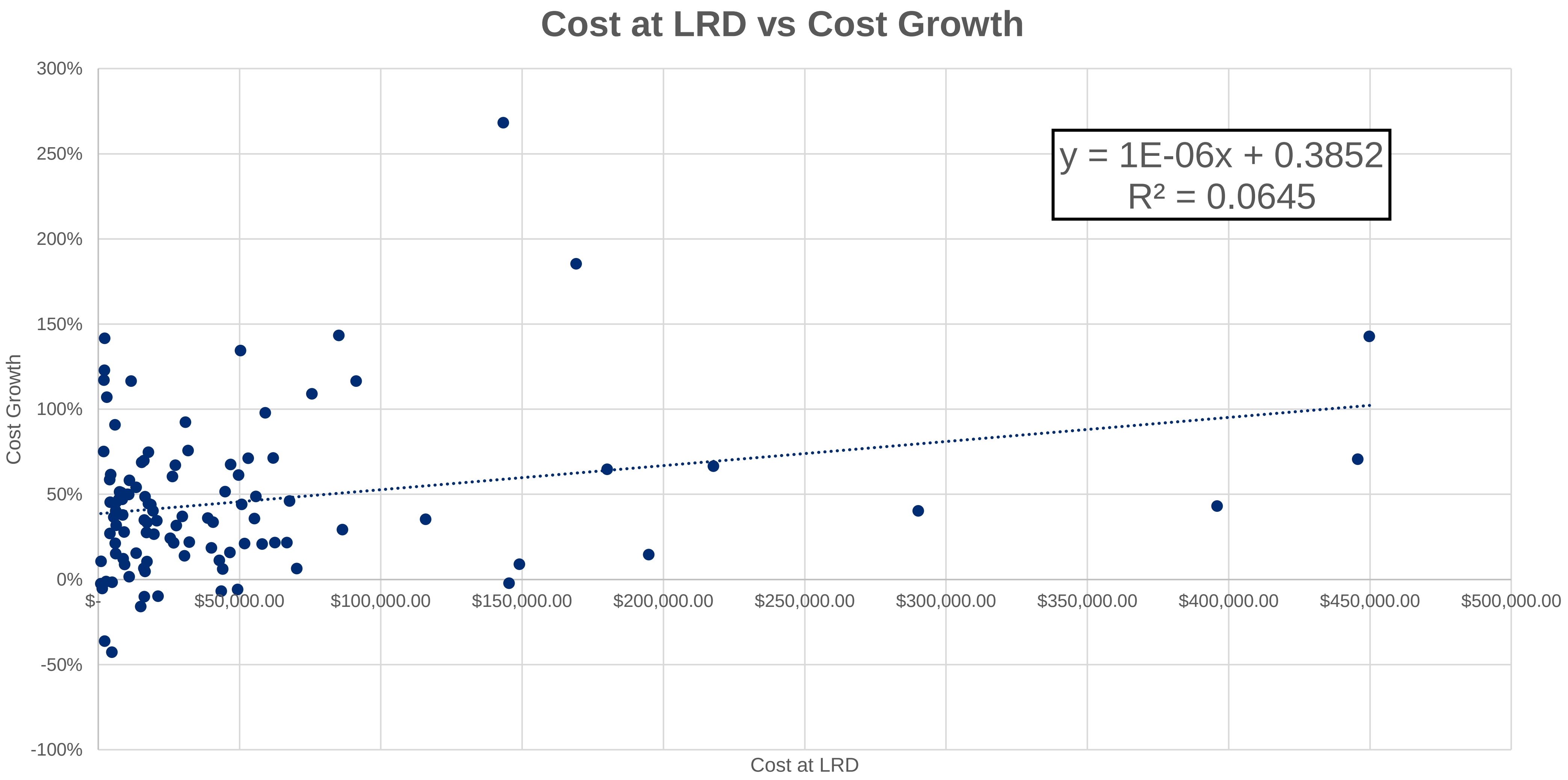
- However, the differences of the averages are not statistically significant. This indicates that regardless of instrument type, there seems to be a tolerance for cost growth that stakeholders are willing to accept

Cost Growth ($) by Instrument Type (Level 1)

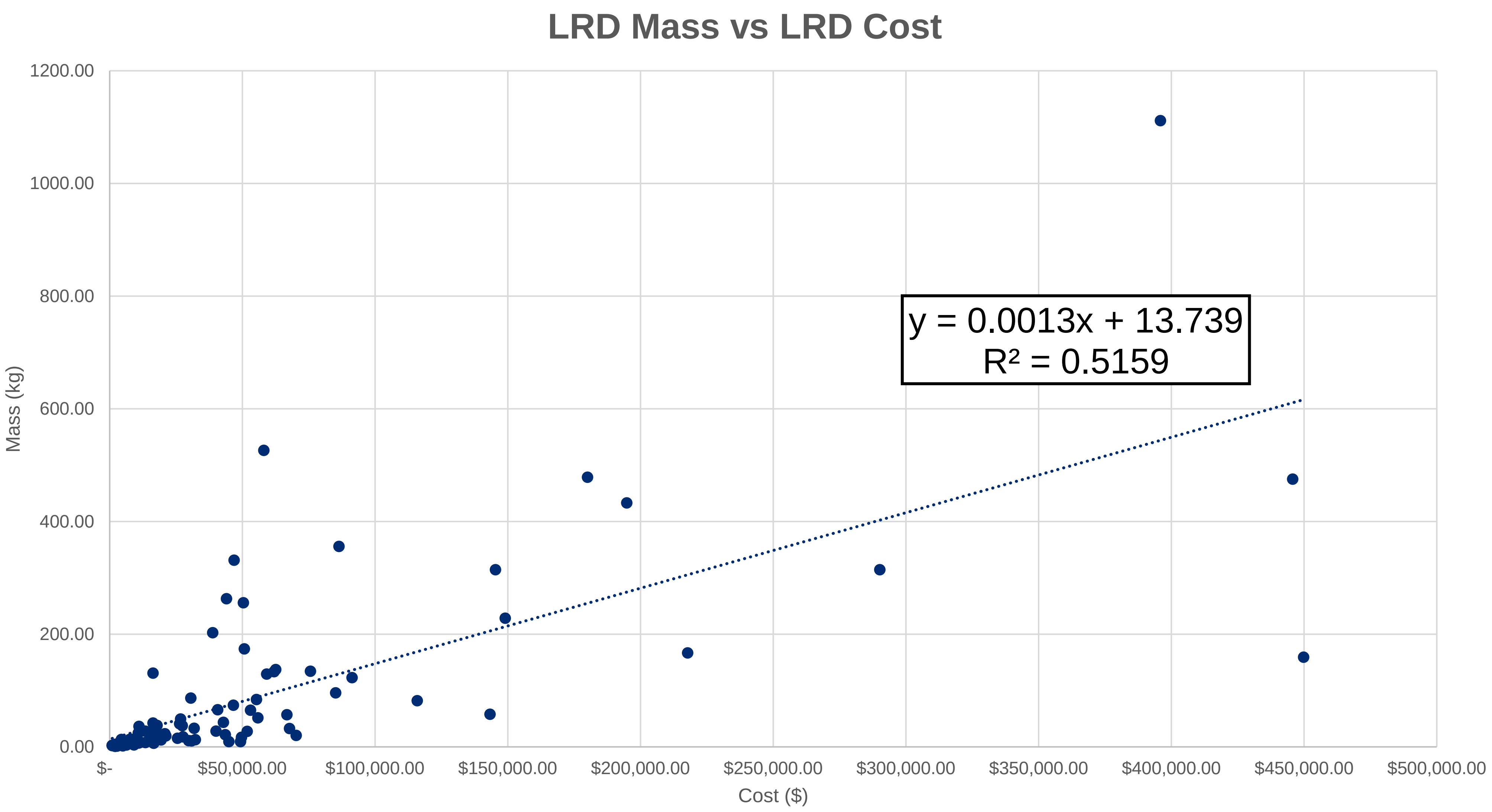
Instrument Type	Average Cost Growth (%)	Average Cost Growth ($)	Average Cost at LRD
Fields Instruments	38%	$1.82M	$13.70M
Particles Instruments	50%	$6.87M	$20.06M
X-Ray Instruments	46%	$14.41M	$48.19M
Optical Instruments	45%	$21.02M	$60.94M
MW/RF Instruments	41%	$31.03M	$101.39M

- Larger, more complex instrument types incur larger cost growth in terms of absolute dollars
- While a percentage tolerance for growth across the various instruments types are similar, applying those similar percentages leads to bigger absolute cost growth for more expensive instrument types

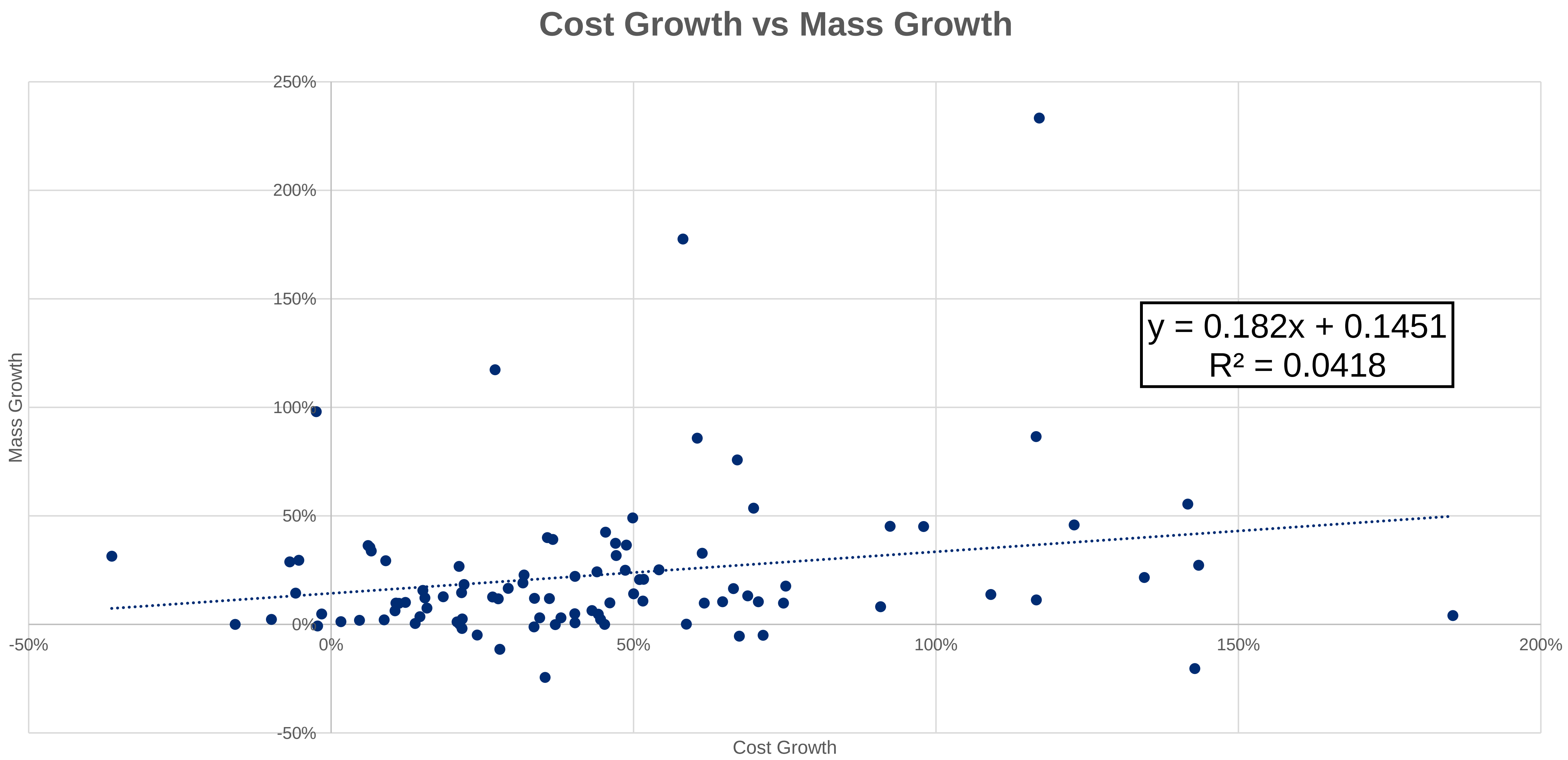
Cost Growth by Total Instrument Cost



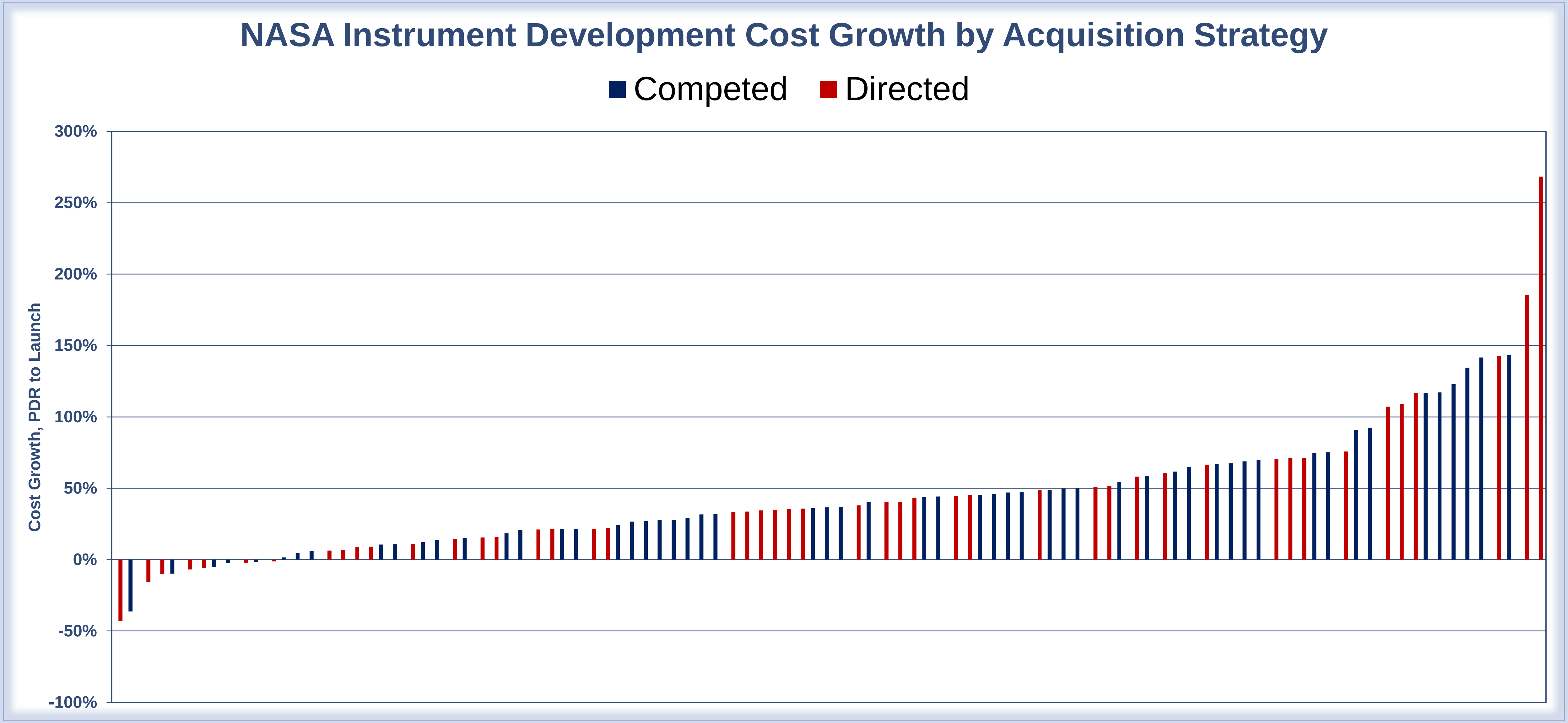
Cost vs Instrument Mass



Cost Growth vs Mass Growth



Cost Growth by Acquisition Strategy

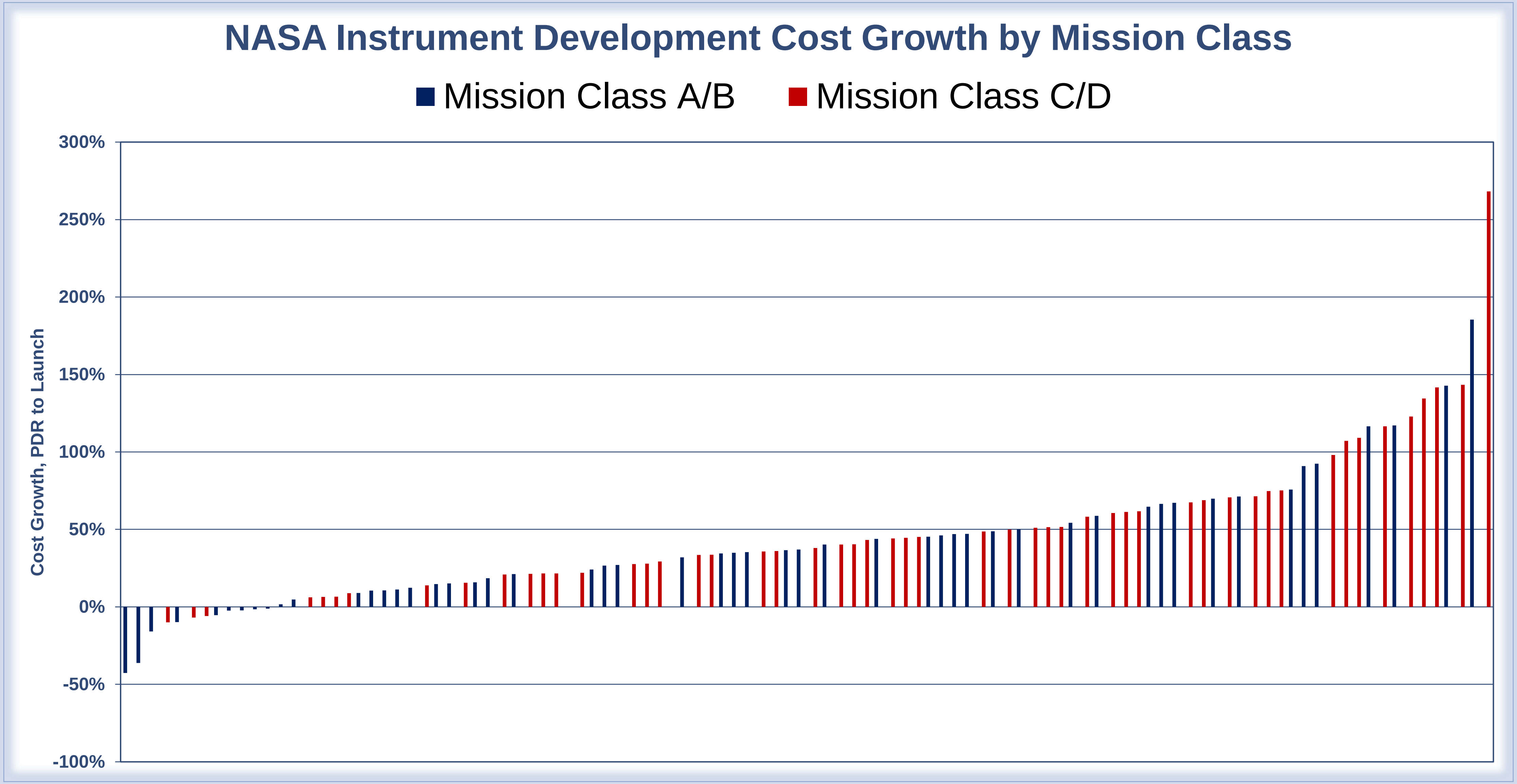


Cost Growth by Acquisition Strategy

Mission Acquisition Strategy	Average Cost Growth
Competed Mission Instruments	45%
Directed Mission Instruments	45%

- At the total mission level, competed missions experience more cost growth than directed missions
- However, regardless of whether a mission is competed or directed, instrument cost growth averages among these two types of mission acquisition strategies are identical so a hypothesis test was omitted
- Stakeholders seem to have similar tolerance for cost growth for instruments on both competed and directed missions

Cost Growth by Mission Class



Cost Growth (%) by Mission Class

Mission Class	Average Cost Growth
Mission Class A/B Instruments	37%
Mission Class C/D Instruments	54%

- $H_0\colon \mu_{A/B} = \mu_{C/D}$
- $H_1\colon \mu_{A/B} < \mu_{C/D}$

T Test Summary	
T statistic	-1.94
P value	0.03

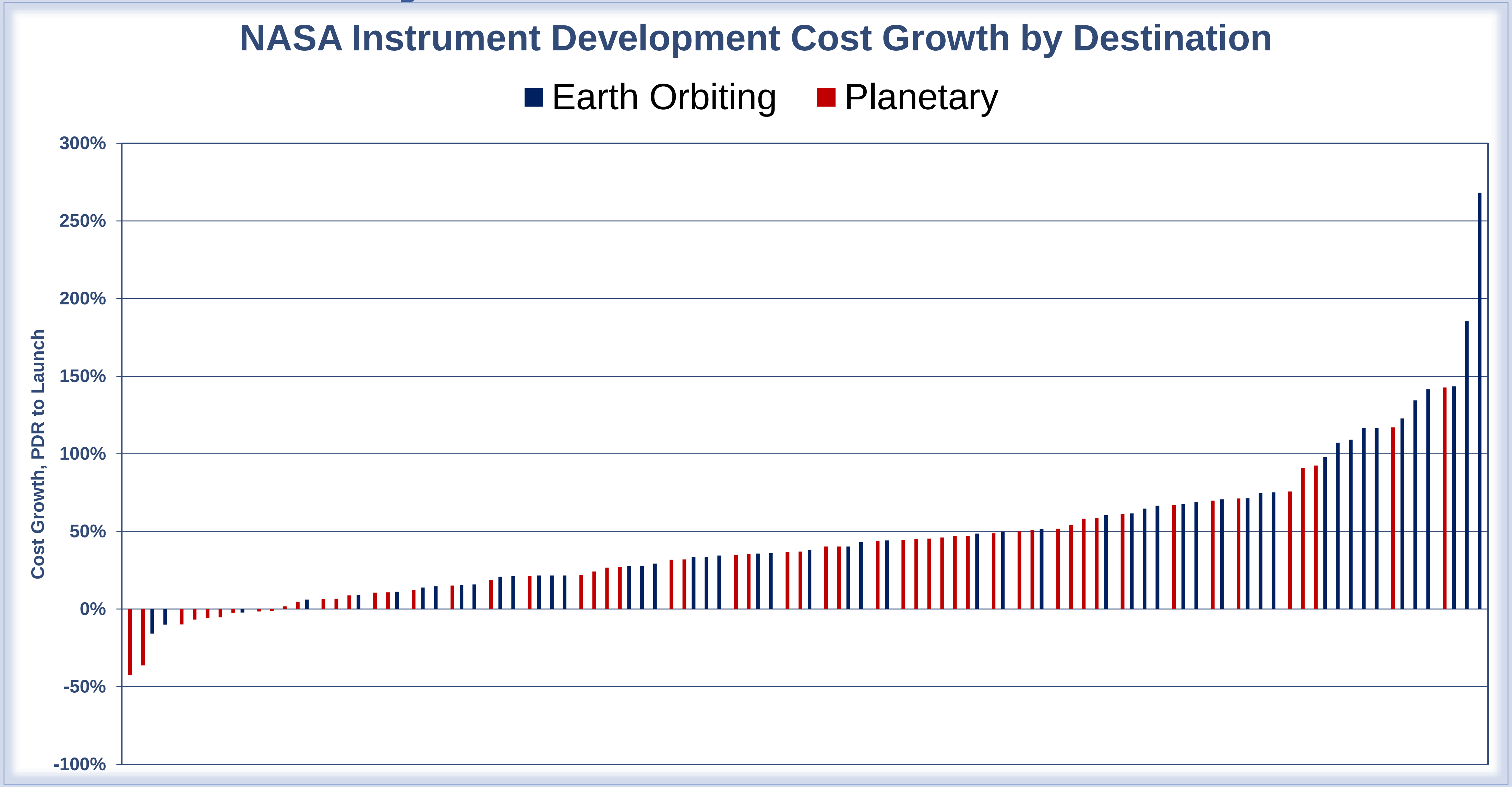
- The difference is statistically significant supporting the assertion that Class C/D instruments experience more cost growth than Class A/B instruments
  - We hypothesized that this difference would be due to lower cost Class C/D instruments resulting in misleadingly higher growth percentages

Cost Growth ($) by Mission Class

Mission Class	Average Cost Growth (%)	Average Cost Growth ($)
Mission Class A/B Instruments	37%	$15.75M
Mission Class C/D Instruments	54%	$17.46M

- Class C/D instruments average more dollars spent than Class A/B instruments
- We speculate that this may be due to higher risk tolerance of Class C/D missions. Higher risk tolerance also means projects are accepting lower cost/schedule reserves levels (often well below 50% confidence) whereas the more expensive Class A/B instruments typically undergo JCL analysis boosting cost reserves to achieve the policy threshold of 70% (or higher) confidence level, thus reducing the likelihood of cost/schedule overrun

Cost Growth by Destination



Cost Growth by Destination

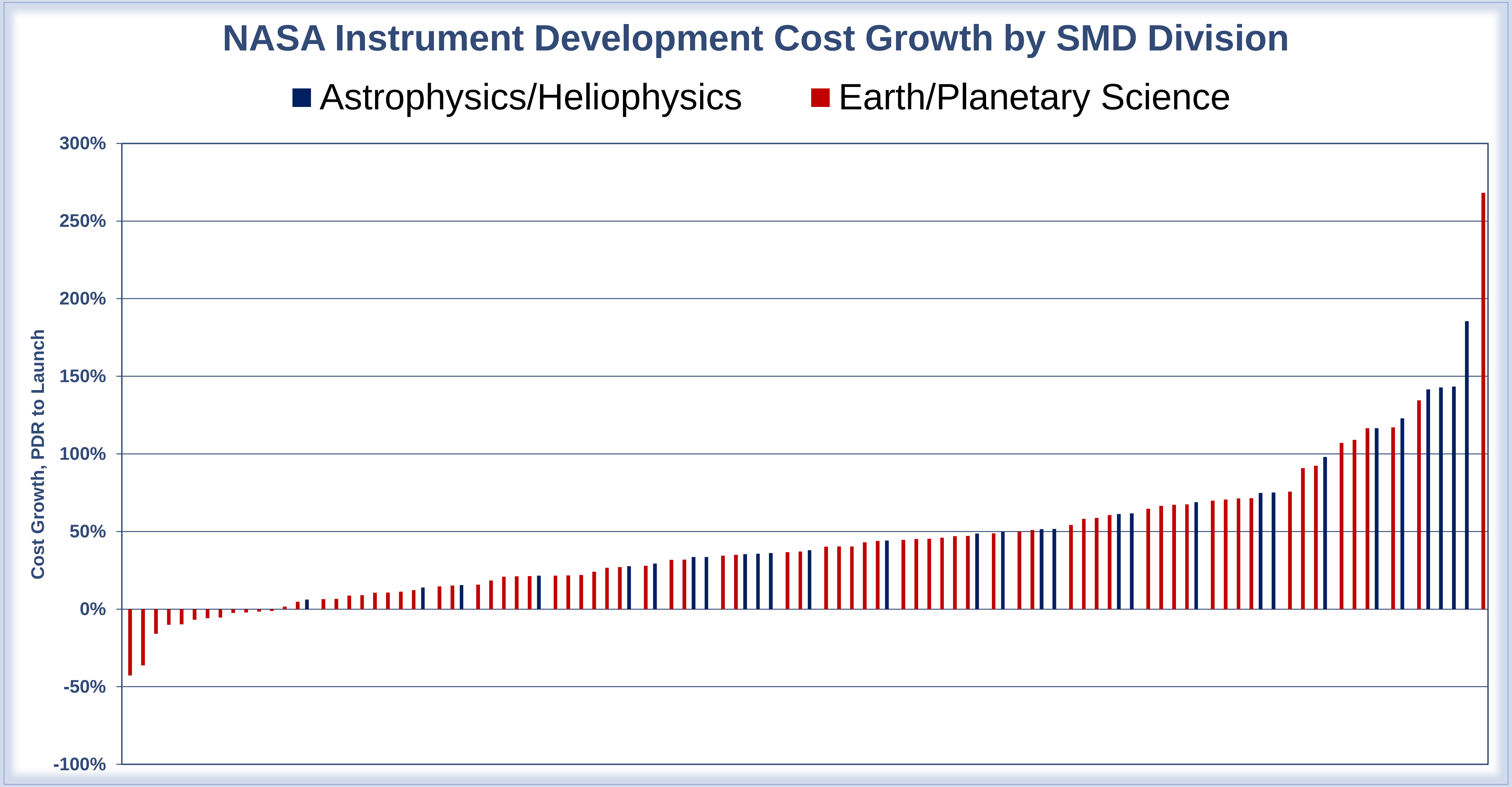
Destination	Average Cost Growth
Earth Orbiting	58%
Planetary	34%

- H_0: $\mu_{earth\ orbiting} = \mu_{planetary}$
- H_1: $\mu_{earth\ orbiting} > \mu_{planetary}$

T Test Summary	
T statistic	2.75
P value	< 0.001

- The difference is statistically significant supporting the assertion that earth orbiting instruments experience more cost growth than planetary instruments
  - We hypothesize that this is due to launch window constraints

Cost Growth by Science Mission Directorate (SMD)



Cost Growth by Science Mission Directorate (SMD)

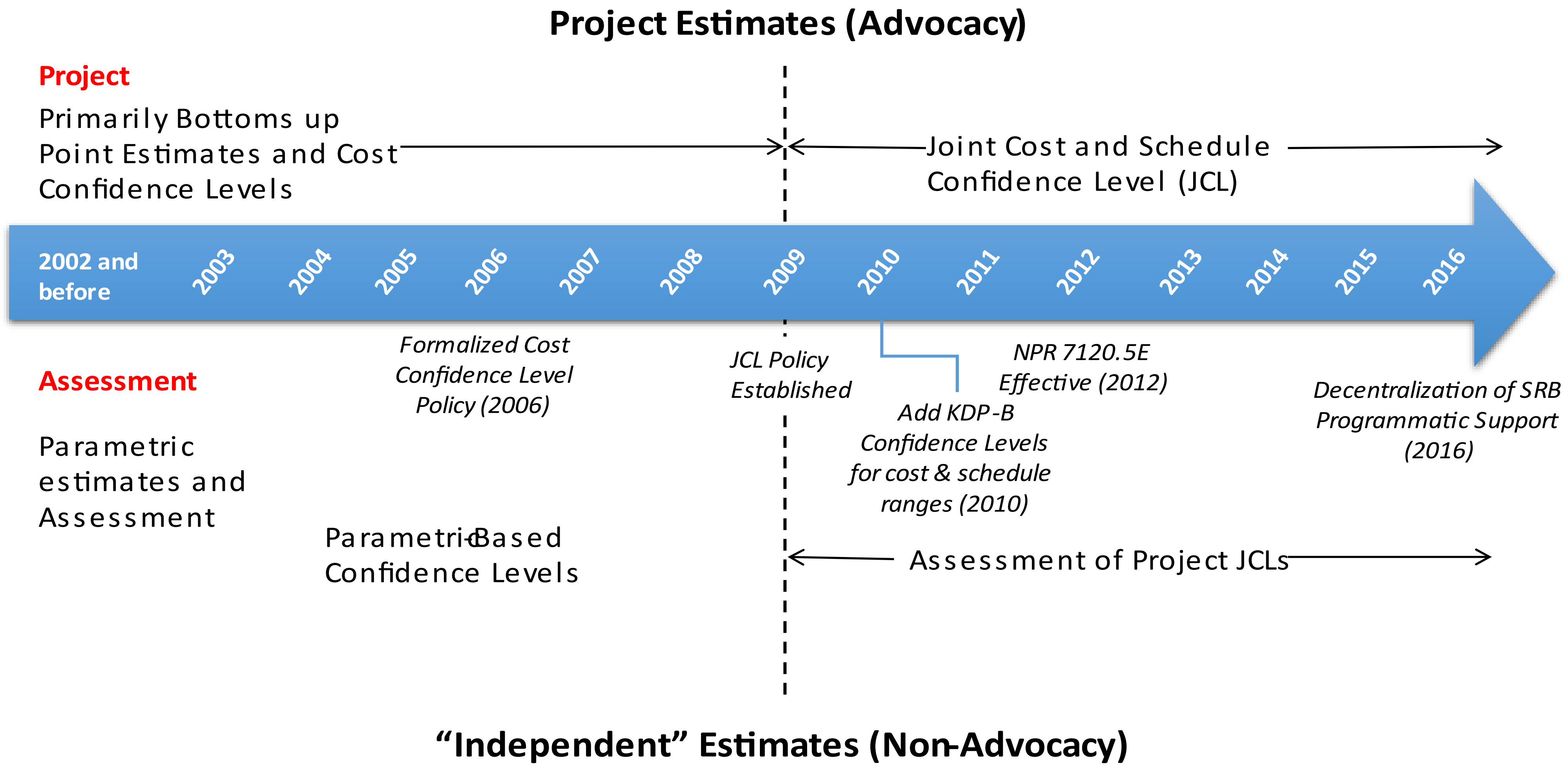
SMD Division	Average Cost Growth
Astrophysics/Heliophysics	64%
Earth/Planetary Science	39%

- $H_0: \mu_{physics\ instruments} = \mu_{science\ instruments}$
- $H_1: \mu_{physics\ instruments} > \mu_{science\ instruments}$

T Test Summary	
T statistic	2.59
P value	< 0.001

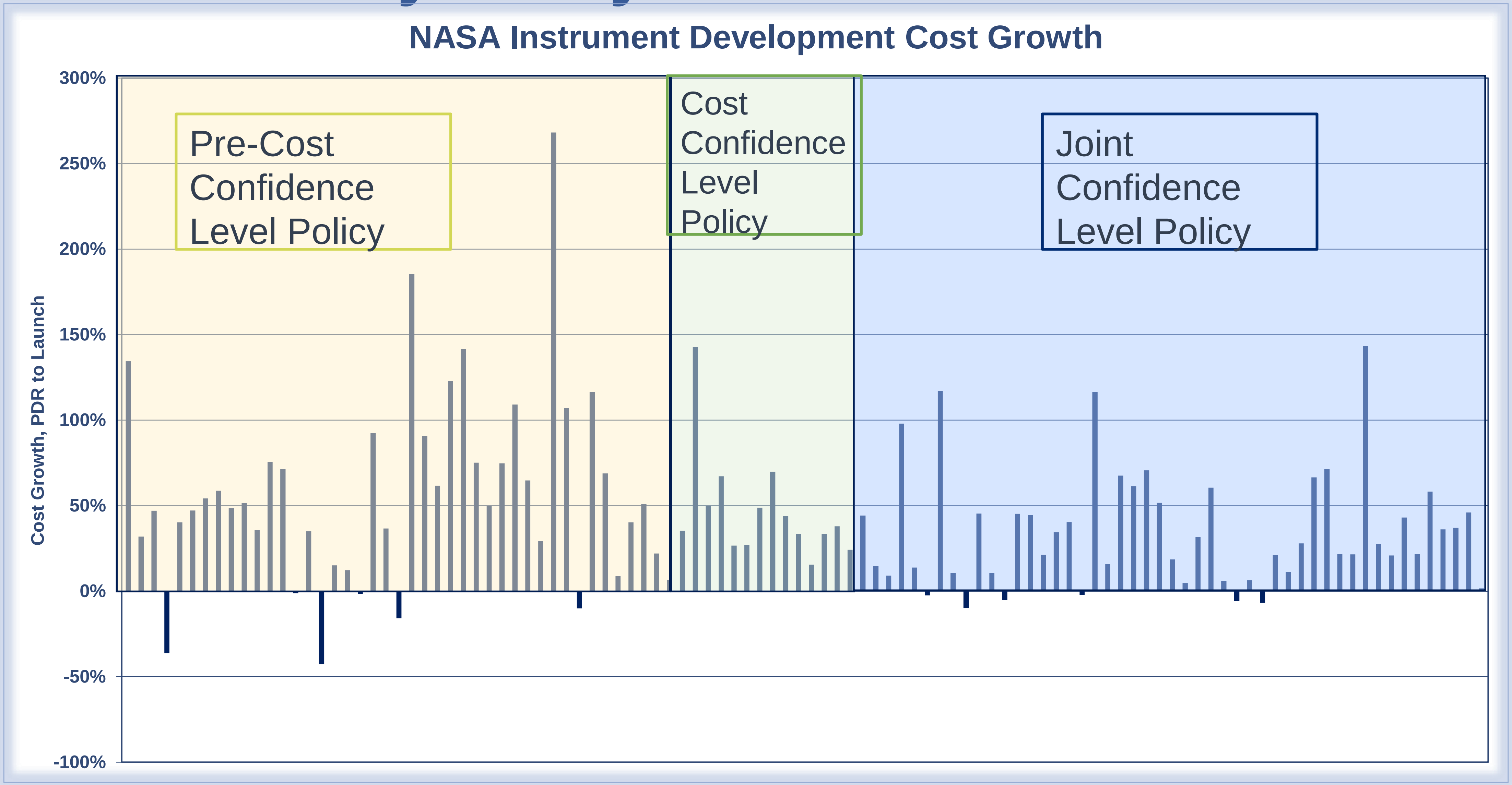
- The difference is statistically significant supporting the assertion that astrophysics/heliophysics instruments experience more cost growth than planetary/earth science instruments
  - Is programmatic tolerance for growth for astrophysics/heliophysics instruments higher?

Evolution of Confidence Level Analysis at NASA



Source: NASA Cost Estimating Handbook Version 4.0

Cost Growth by Policy Era



Cost Growth by Policy Era

JCL Establishment	Average Cost Growth
Pre-JCL	55%
JCL	35%

- $H_0: \mu_{pre-JCL} = \mu_{JCL}$
- $H_1: \mu_{pre-JCL} > \mu_{JCL}$

T Test Summary	
T statistic	2.38
P value	< 0.001

- The null hypothesis is rejected supporting the assertion that pre-JCL instruments experience more cost growth than JCL instruments

Regardless of how you look at it, cost growth decreasing over time is apparent. A major conclusion can be made that the new programmatic requirements put in place have helped NASA control cost growth for instruments.

Analysis of all Factors

	Cost Growth	*Mission Class*	*JCL*	*Destination*	*SMD Division*
Cost Growth	100%				
Mission Class	19%	100%			
JCL	22%	-7%	100%		
Destination	26%	49%	-13%	100%	
SMD Division	18%	55%	7%	39%	100%

- Previous slides showed how instrument cost growth relates to single variables
- In reality, cost growth is driven by several variables, some of which may be correlated with each other
- Future work will be to perform this multi-variable analysis

Reported Development Issues

- To capture cost issues associated with the natural progression of instrument design, a review of project Monthly Status Reports (MSRs) was conducted for the 106 NASA instruments in our dataset spanning ~20 years of development history
- Hundreds of project monthly status reports were examined to identify trends for major instrument issues and problems
- For each project, a sample of four to five monthly reports per year of development were reviewed
- The analysis only looked at manifested instrument problems requiring project intervention to mitigate

Classification Methodology

- The 2008 NASA Instrument Capability Study (NICS) provided the foundation for categorizing and coding instrument development issues
- There are five major themes
- Each theme has up to six subcategories for a total of 21 subcategories
- The review yielded ~200 observations of problems and issues

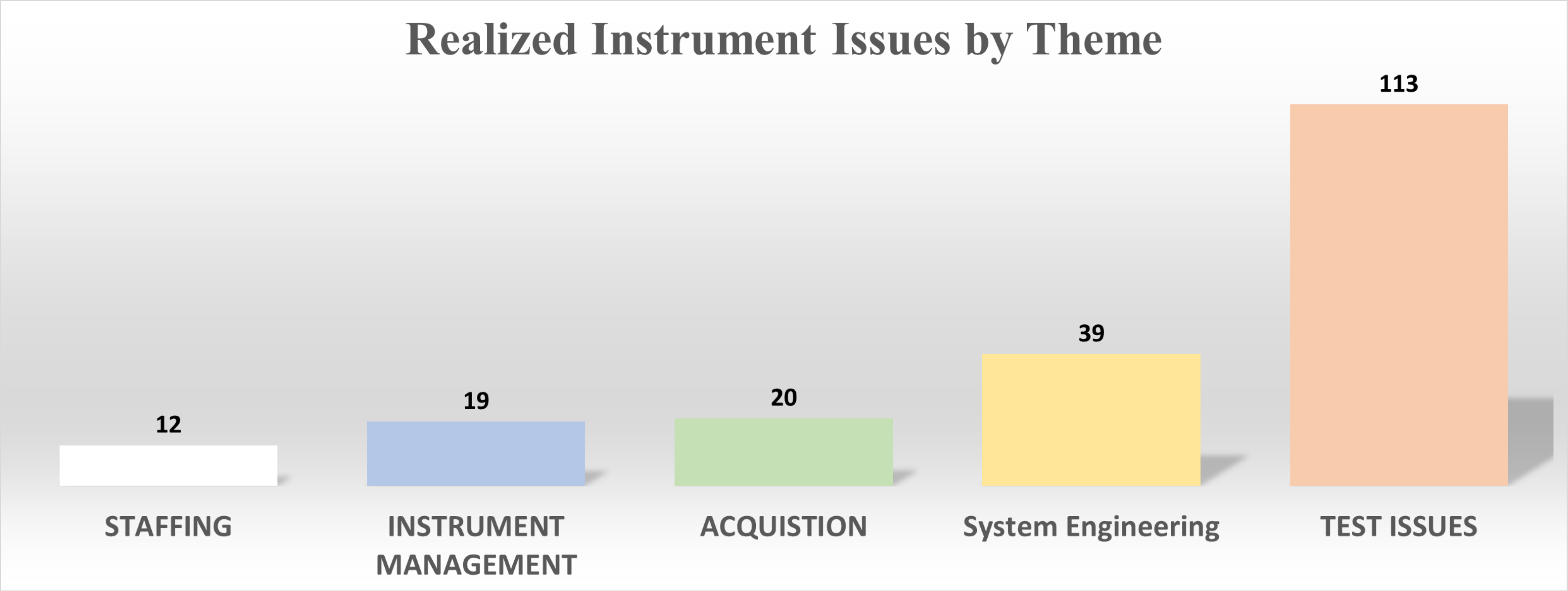
THEME	CODE	DESCRIPTION
STAFFING	ST-1	Instrument Leadership Issues
	ST-2	Instrument Teams Understaffed
	ST-3	Difficulty Acquiring Critcal Skills
	ST-4	Difficulty Rolling Staff Off
ACQUISTION	AQ-1	Insufficient Resources: Optimistic/Unrealistic Estimates
	AQ-2	Supply Chain Issues: Subsystem/Compenent/Vendor
SYSTEMS ENGINEERING	SE-1	Requirements Management Problems: Proceeding at risk, Lack of Reqts flow down
	SE-2	Requirements Formulation Issues: Technical Complexity Incl Mass Power Issues
	SE-3	Issues with Requirements Changes: Redesign/Changes occuring after PDR and or CDR
	SE-4	Risk Management Issues: Risks not identified early, Mitigation plans not developed early
	SE-5	Review Effectiveness: Objectives not meet in reviews, Not raising issues at reviews
INSTRUMENT MANAGEMENT	IM-1	Issues with Instrument Reserves: Lack of Cost/Schedule Reserve Authority
	IM-2	External Factors
	IM-3	Issues with Lines of Communication Issues: Lines of Authority
	IM-4	Issues with Budget & Schedule Management at Subsystem Level
TEST ISSUES	TI-1	Unverifyable Requirements
	TI-2	Testing Took Longer
	TI-3	Aggresvie Schedule
	TI-4	Test Failures
	TI-5	Workmanship & Technical Problems
	TI-6	Problems with GSE, Test Equip

Source: NASA Instrument Capability Study

Issue Classification Examples

Issue		Code	Classification
Personnel could be forced to work excessive daily/weekly/monthly hours in order to maintain an on-time schedule/delivery.	→	**ST-2**	**Instrument Teams Understaffed**
Payload vent valve receipt has slipped due to procurement problems with valve.	→	**AQ-2**	**Supply Chain Issues: Subsystem/Compenent/Vendor**
Telescopes need to be repaired or redesigned to account for mechanical analysis issue.	→	**SE-3**	**Issues with Requirements Changes: Redesign/Changes occuring after PDR and or CDR**
Development cost continually increasing. Reserves will not be available to address emerging fabrication issues.	→	**IM-1**	**Issues with Instrument Reserves: Lack of Cost/Schedule Reserve Authority**
The detector electronics experienced an anomaly while in thermal vacuum testing. The detector data shows two anomalous conditions; a loss of an analog signal and the loss of a digital signal in the detector electronics sub-assembly.	→	**TI-4**	**Test Failures**

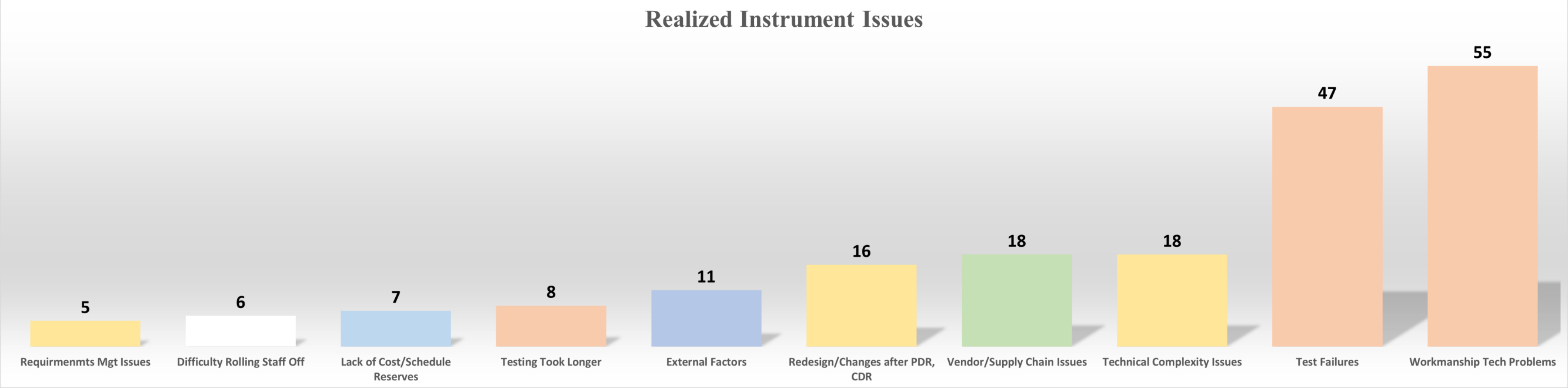
Number of Issues by Theme



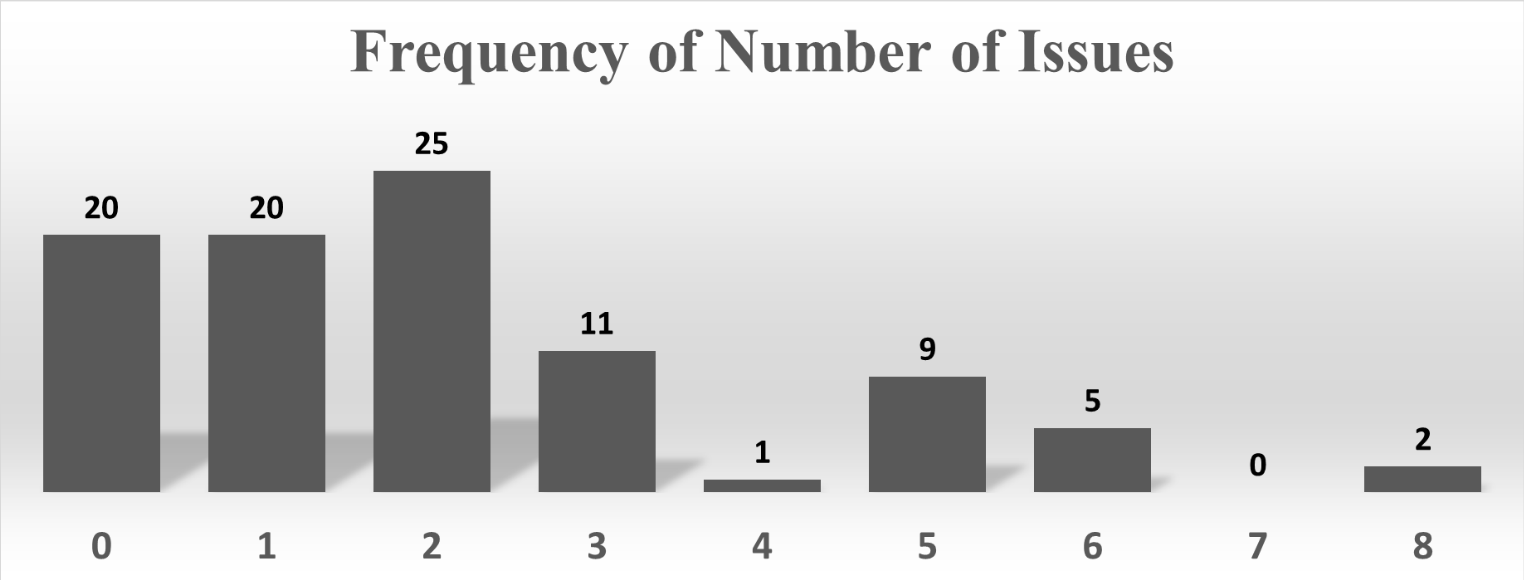
- Test issues account for 56% of the documented issues

Issues by Subcategory

- The most prominent subcategories that have contributed towards observed cost growth using the project monthlies are shown below
- Workmanship Issues and Test Failures, accounting for 27% and 23% of the issues, respectively. The remaining eighteen subcategories had issues that were single digits on a percentage basis



Number of Issues



- The average number of issues for each instrument is 2 with each instrument ranging from 0 to 8 issues
- Total number of issues and cost growth is correlated at 33%

Cost Growth by Test Issue

Test Issue	Average Cost Growth
Instruments w/ TI-4 or 5	54%
Instruments w/out TI-4 or 5	30%

- H_0: $\mu_{TI-4/5} = \mu_{No\ TI-4/5}$
- H_1: $\mu_{TI-4/5} > \mu_{No\ TI-4/5}$

T Test Summary	
T statistic	2.82
P value	< 0.001

- The difference is statistically significant supporting the assertion that instruments with TI-4 or 5 issues experience more cost growth than instruments without TI-4 or 5 issues
  - We hypothesized that this may be due to high-level differences in programmatics being correlated with lower-level test issues (as seen on the next slide)

Correlation Analysis

	Cost Growth	Mission Class	JCL	Environment (EO vs PL)	SMD Division	Test Issue
Cost Growth	100%					
Mission Class	16%	100%				
JCL	23%	-12%	100%			
Environment (EO vs PL)	25%	44%	-16%	100%		
SMD Division	15%	48%	0%	31%	100%	
Test Issue	25%	26%	22%	10%	22%	100%

- We wanted to evaluate if high-level differences in programmatics could be positively correlated with lower-level test issues
- If an instrument has a test issue (TI 4 or 5), that instrument is 25% more likely to experience cost growth, 26% more likely to be Mission Class C/D, and 22% more likely to be from an older policy era
- Newer policies and higher mission classes drive down risks including risks seen during testing and cost growth in general
  - Thus, testing issues corresponding with lower mission class and antiquated policy era justifies why newer policies are successful as well as how the added requirements of higher-class missions does indeed drive down risk of cost growth

Conclusions

- The goal of this study was to examine cost growth of NASA instruments ranging in size and scope
  - 87% of instruments experienced cost growth post-PDR
  - The average NASA instrument experienced 46% cost growth post-PDR
- This study highlights many potential areas of cost growth. While instrument type and mission acquisition strategy are both not statistically significant, mission class, destination, SMD division, and policy era are all statistically significant
- Thus, there are many factors that may contribute towards instrument cost growth

Key Findings

- Instrument cost growth has been greatly reduced as NASA has implemented updated programmatic policies, as seen by the impact of the JCL policy era data
  - Note that we have also seen this reduction in growth at the mission level (Sholder, 2023)
- In the statistical analysis of potential variables impacting cost growth, high-level technical variables (such as instrument type) were not significant, but many high-level programmatic variables (such as mission class and policy era) were
- When you look at realized instrument issues from MSRs, the primary issues are technical, although at a lower-level (i.e., test failures)
- There appears to be some connection given the substantial correlations between high-level programmatic variables and lower-level technical variables

Potential Future Work

- Examining lower-level instrument categories further
  - Some diagnostic tests revealed a distinction between active and passive microwave instruments, but the difference was not statistically significant
- Evaluating cost growth among instruments that were designed and developed in-house compared to instruments that were designed and developed out-of-house through other NASA centers, academic institutions, prime contractors, and research laboratories
- Evaluating cost growth at the payload level
  - It’s a brand new question to look at payload growth given that some instruments in a specific mission may experience cost growth while others could experience cost shrinkage

JOHNS HOPKINS

APPLIED PHYSICS LABORATORY

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