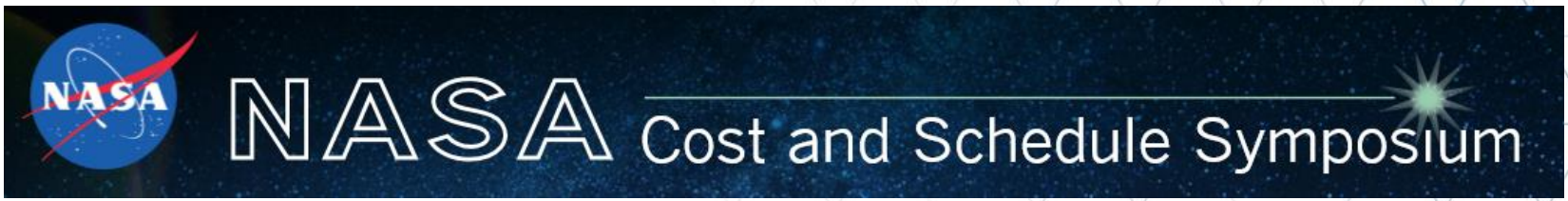
JOHNS HOPKINS
APPLIED PHYSICS LABORATORY



Competed vs Directed Missions, Tigers, and Bears, oh my

2023 NASA Cost & Schedule Symposium

NASA Jet Propulsion Laboratory

Rachel Sholder & Sally Whitley
Johns Hopkins Applied Physics Lab
Parametric Cost Analyst

Agenda

- Background/History
- Methodology
- Cost Growth Analysis
  - Program Line
  - Science Mission Directorate Division
  - Policy Era
- Schedule Growth Analysis
- Conclusion

History of Mission Formulation

- Initially, NASA managed all projects and developed all spacecraft while scientists had the opportunity to manage science instruments and data analysis on a mission
- The idea of competed missions arose with the goal of soliciting mission ideas from the broadest possible community including ideas that are not included in NASA's long-term strategic plans
- The hope was that competed missions would allow investigation teams to form based on the unique science and engineering skills required to achieve a particular mission's science objectives
- This would give scientists more autonomy and freedom in the decision making process and management of developing space missions
- This would also encourage an efficient and minimum-cost implementation approach to a mission concept via strict cost caps

Source: Principal-Investigator-Led Missions in the Space Sciences (2006)

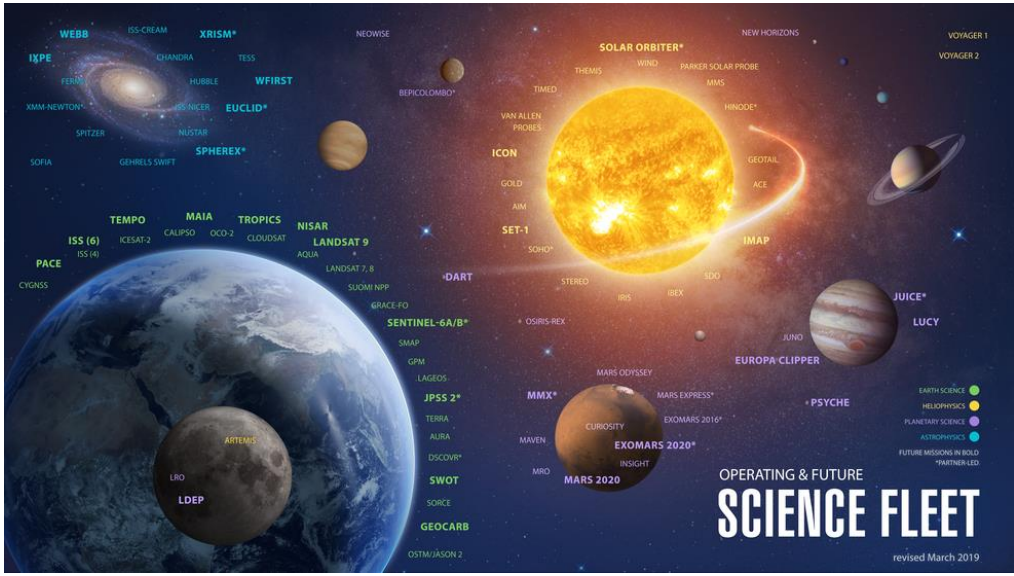
History of Program Lines

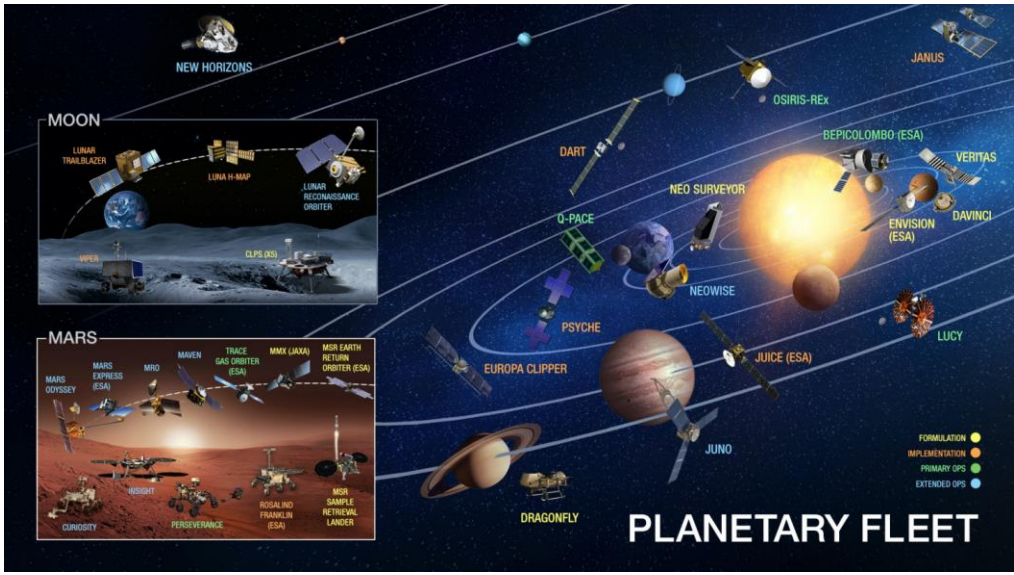
- In the early to 1990s, NASA created new mission programs to offer scientists and engineers the opportunity to lead their own space science missions
- As a first step, NASA introduced the Discovery program
- Then, NASA transitioned the existing Explorer program to a competed program
- In early 2000, NASA introduced the Mars Scout program, which has since been retired, and the New Frontiers program
- Lastly, the Earth System Science Pathfinder (ESSP) program was established including the Earth Venture Mission (EVM) and Earth Venture Instrument (EVI) programs

Source: Principal-Investigator-Led Missions in the Space Sciences (2006)

Background

- When projects are initiated, they are either assigned directly to a NASA Center or implementing organization by the Mission Directorate or are selected through a competitive process such as an Announcement of Opportunity (AO)
  - **Directed Missions**: Missions assigned directly to a NASA Center or implementing organization by the Mission Directorate
  - **Competed Missions**: Missions selected through the AO process. Competed missions typically have a prescribed cost cap prior to award and are led by a Principle Investigator.





Text Source: NASA Procedural Requirements 7120.5F 2.1.3.2
Image Source: NASA

One Prior Study

- The Discovery missions in the dataset had average life-cycle cost growth of 14%
- The directed missions in the dataset averaged 18% life cycle cost growth

TABLE 5.1 Cost Growth for Discovery Missions (million $)

	Life-Cycle Cost			Development Cost		
Mission	CAR	Current	% Change	CAR	Current	% Change
NEAR	262.8	234.4	−10.8	161.9	124.9	−22.9
Mars Pathfinder	273.2	262.3	−4.0	199.2	199.2	0.0
Lunar Prospector	62.9	69.4	10.3	29.8	27.6	−7.4
Stardust	206.1	209.1	1.5	117.8	116.7	−0.9
Genesis	216.6	272.3	25.7	125.4	151.2	20.6
CONTOUR	154.3	140.7	−8.8	79.1	84.8	7.2
MESSENGER	314.0	422.5	34.6	162.5	200.0	23.1
Deep Impact	279.2	332.5	19.1	156.6	213.8	36.5

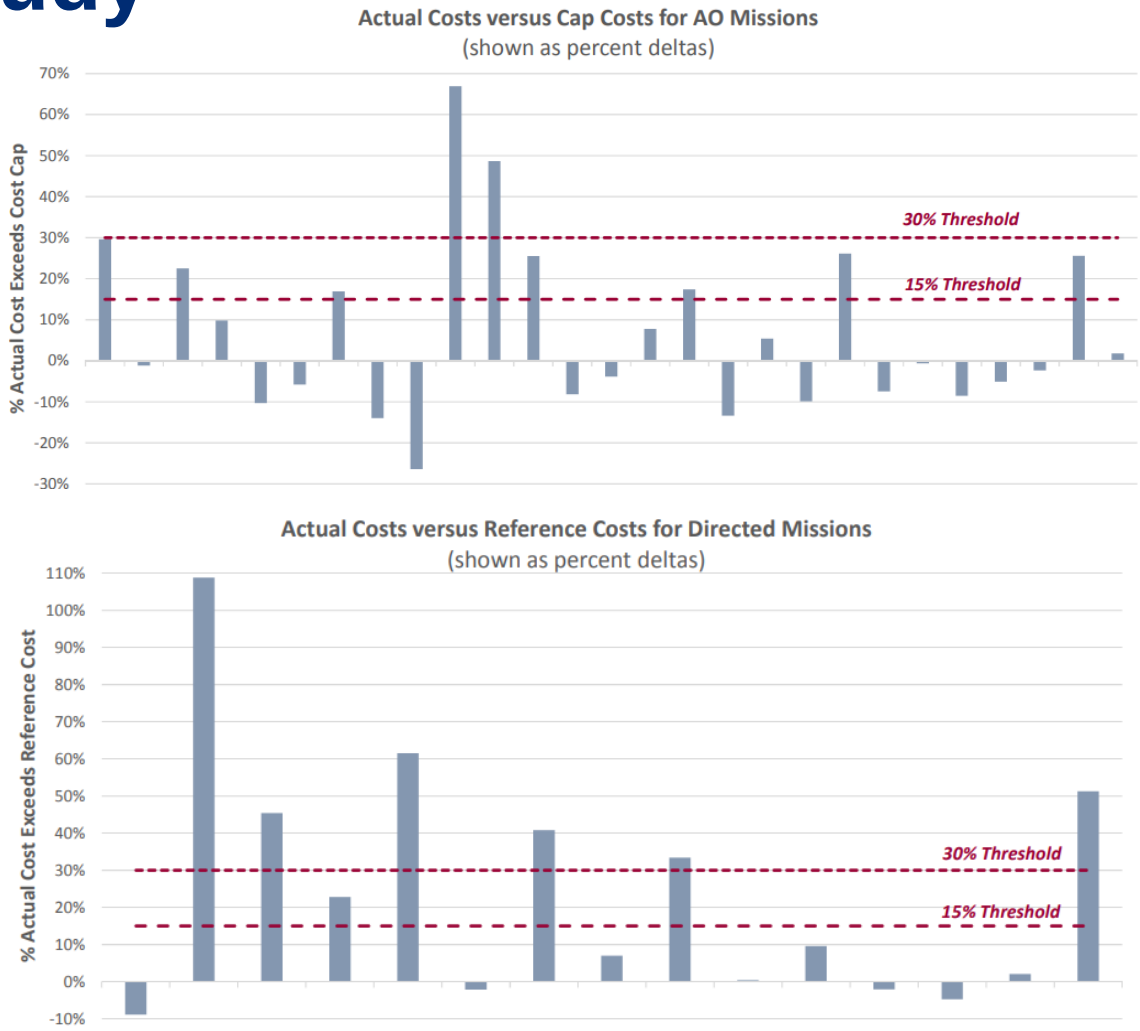
TABLE 5.3 Cost Growth for Selected NASA Core Missions (million $)

	Life-Cycle Cost[a]			Development Cost			Launch Date	
Mission	CAR	Current	% Change	CAR	Current	% Change	CAR	Actual
Mars Global Surveyor	231.3	298.8	29.2	132.3	132.3	0.0	11/96	11/96
Mars Climate Orbiter	353.3	276.2	−21.8	193.1	193.1	0.0	12/98	12/98
Mars Odyssey	418.8	438.2	4.6	287.9	309.3	7.4	4/01	4/01
Mars Exploration Rovers	646.4	809.9	25.3	449.6	606.8	35.0	6/03	6/03
Spitzer Space Telescope	797.6	1,233.2	54.6	392.8	635.9	61.9	12/01	8/03
TIMED	198.1	233.4	17.8	129.3	162.3	25.5	5/00	12/01

Tables from Principal-Investigator-Led Missions in the Space Sciences (2006)

Another Prior Study

- Looked at actual costs versus cost caps (AO or KDP-B) for competed missions
- Looked at actual costs versus reference costs (KDP-A or B) for directed missions
- Found that competed missions had better cost performance than directed missions



Figures from "Cost Performance of AO Missions" by Marc Greenberg (2019)

Motivation

- It is often thought that competed missions experience less cost growth than directed missions
  - This is supported by the Greenberg study aforementioned
- Over the years, there has been lots of interest and debate over Greenberg's findings
- A criticism of the previous study's methodology was the absence of standardization in selecting baseline comparison costs
  - Earliest known estimates were different among missions
  - Launch vehicle and operations costs were treated differently depending on the mission
- This study seeks to address the criticism

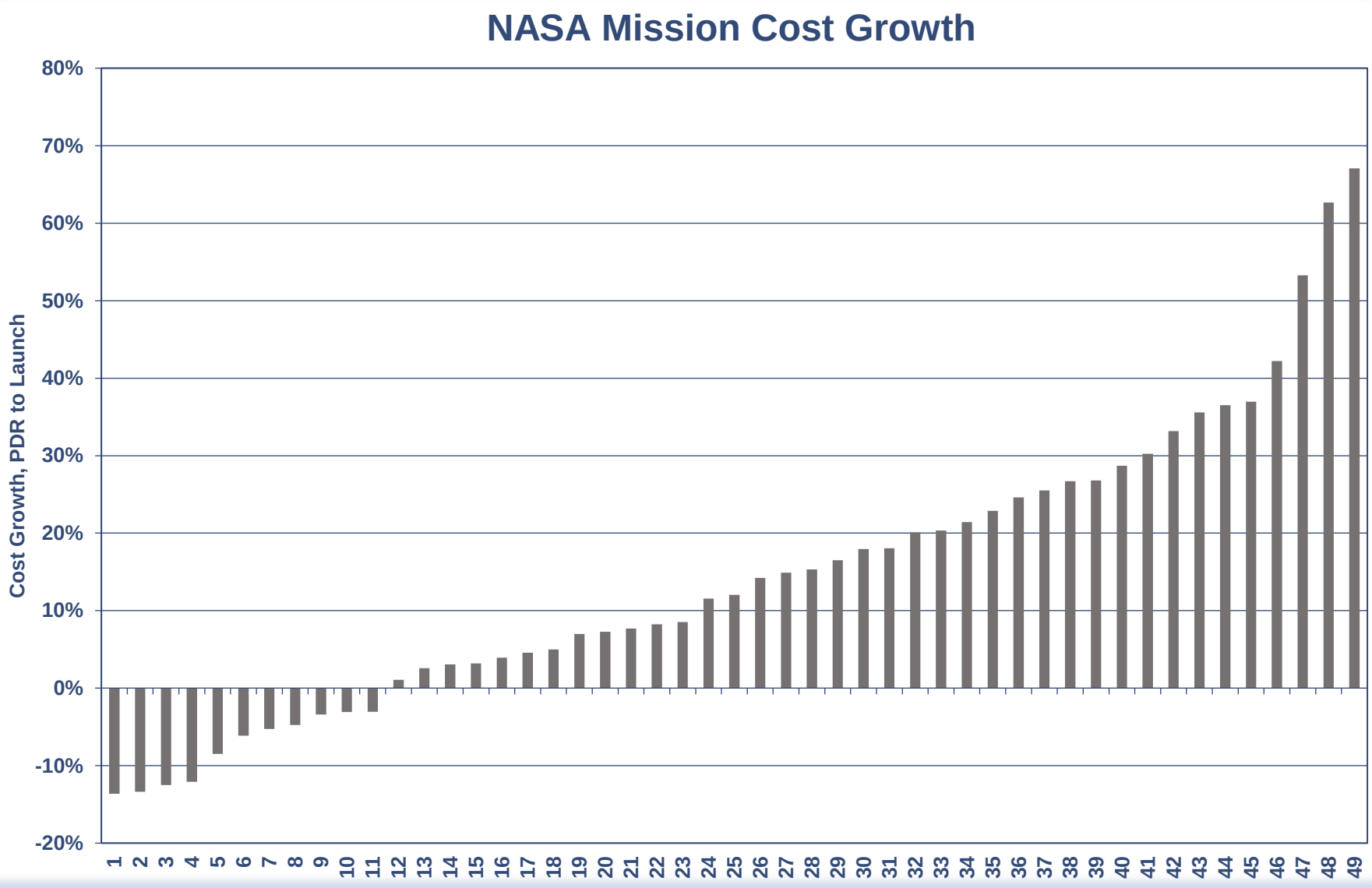
Methodology: Data Collection & Normalization

- Cost data collected via PDR and Launch CADRes (Part C)
- Programmatic data collected via CADRes (Parts A, B)
- Initially looked at a total of 52 robotic missions:
  - Launch dates from 2001 to 2023
  - Total development costs up to $1B FY23
- Costs were normalized:
  - Phases A-D
  - Exclude launch vehicle costs, HQ UFE, and contributions
  - Include reserves

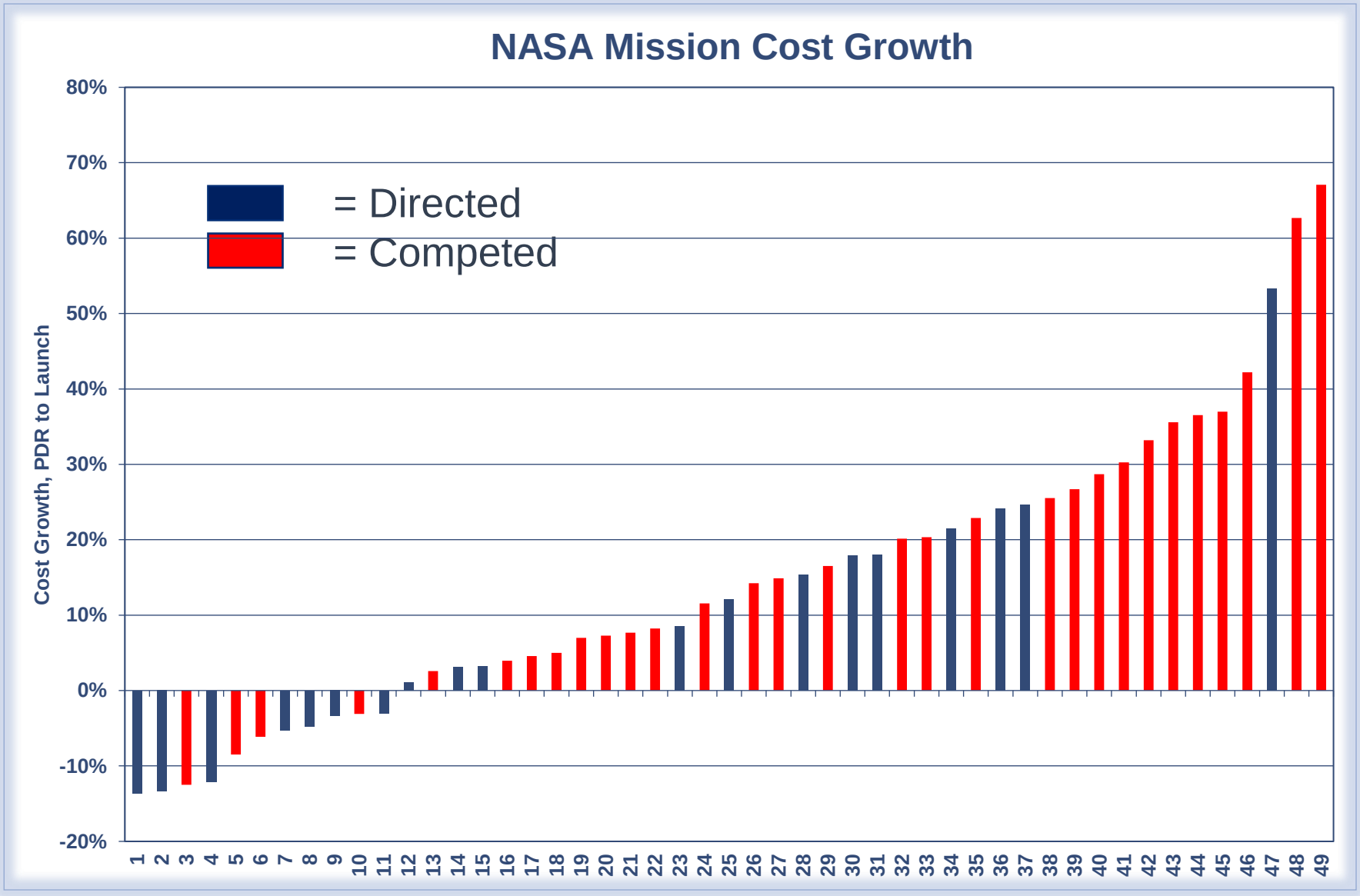
Methodology: Data Collection & Normalization

- Split the dataset up into “Competed” versus “Directed” missions
  - 31 competed missions
  - 21 directed missions
- Cost growth was calculated from PDR to Launch as:
  - $cost\ growth = \frac{(Cost\ @\ Launch - Cost\ @\ PDR)}{Cost\ @\ PDR}\ x\ 100\%$
- Performed outlier tests on both groups
  - Removed 1 mission from the competed dataset for a total of **30 competed missions**
  - Removed 2 missions from the directed dataset for a total of **19 directed missions**

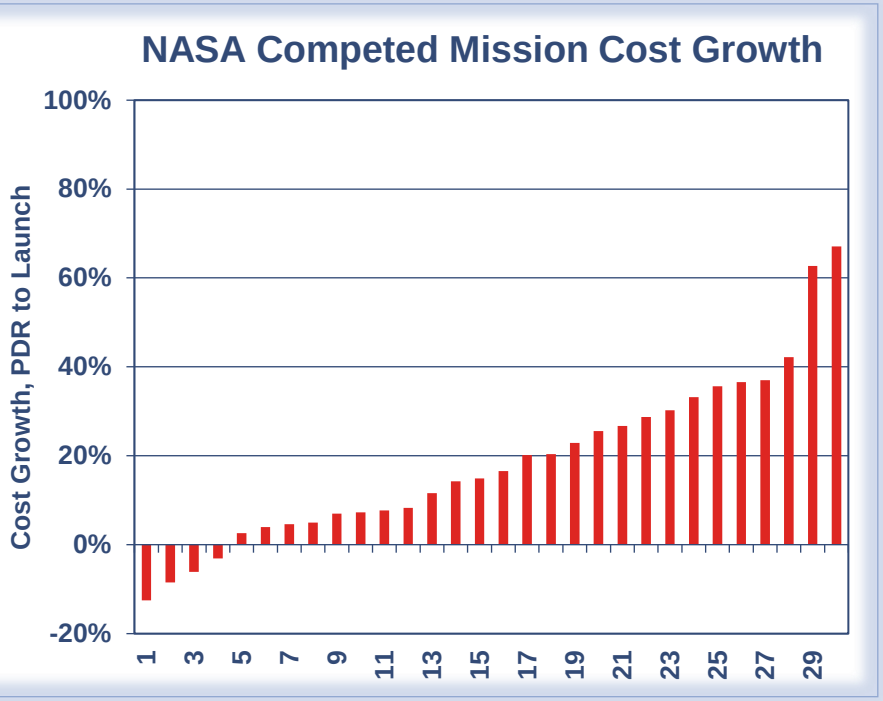
Math is Hard/EZIE

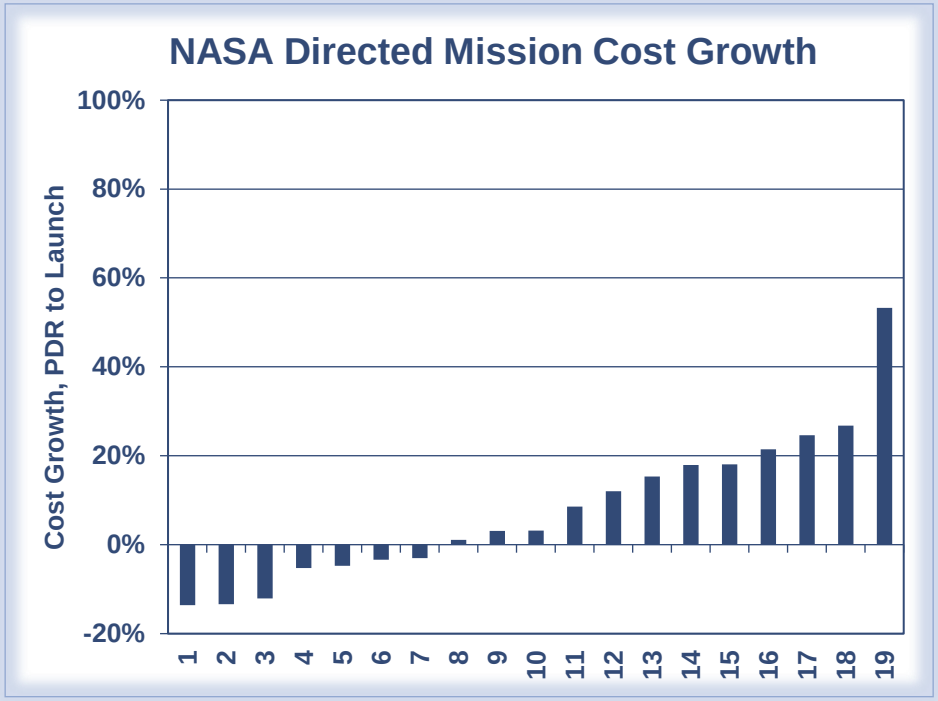


Competed versus Directed Missions



Competed vs Directed Cost Growth



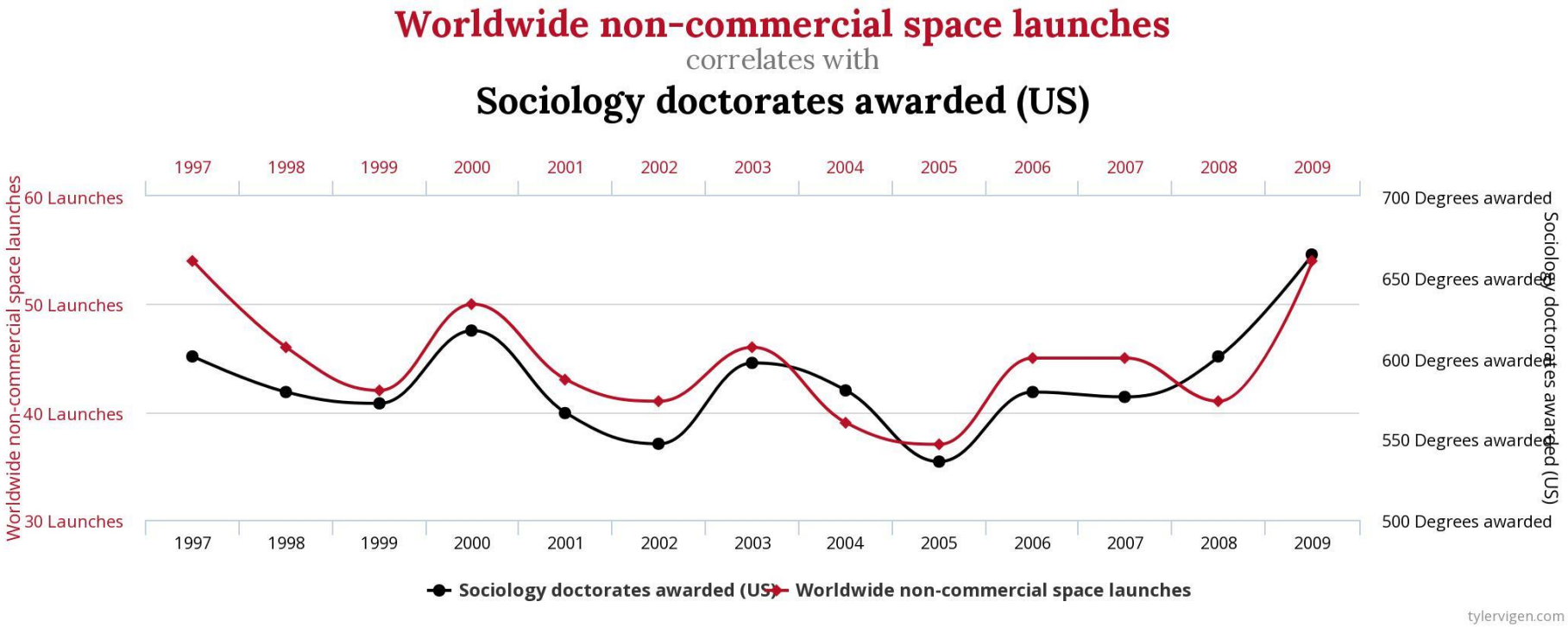


Competed Mission Summary Statistics	
Mean	19%
Median	16%
Standard Deviation	0.19
Minimum	-12%
Maximum	67%

Directed Mission Summary Statistics	
Mean	8%
Median	3%
Standard Deviation	0.17
Minimum	-14%
Maximum	53%

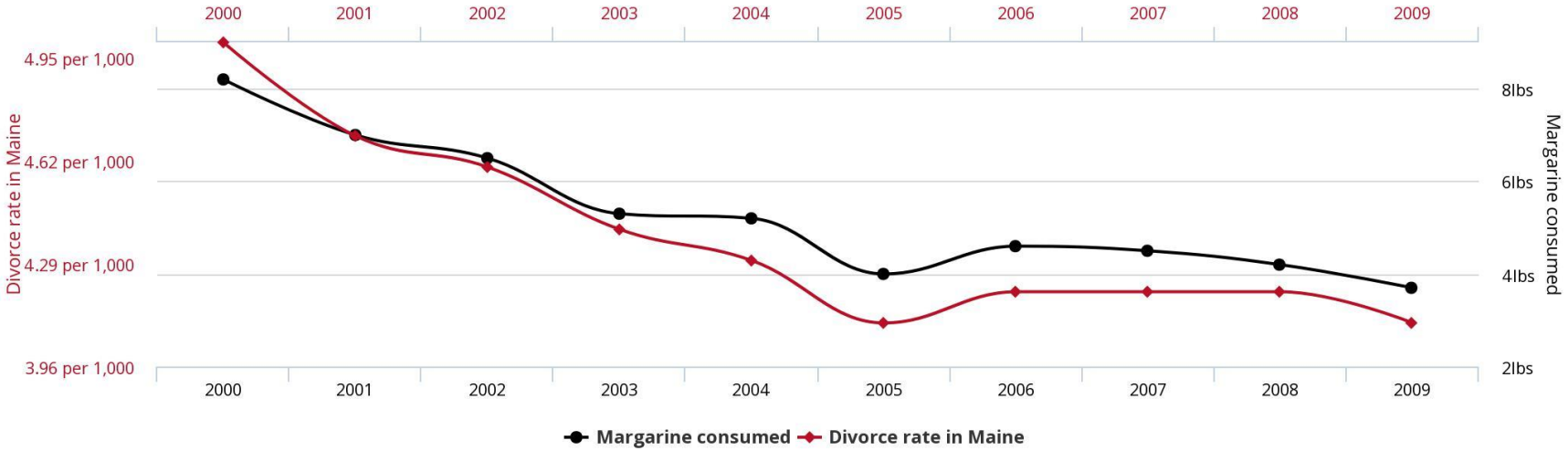
Spurious Correlations

- Spurious correlation (noun): a mathematical relationship between two variables that occurs purely by chance

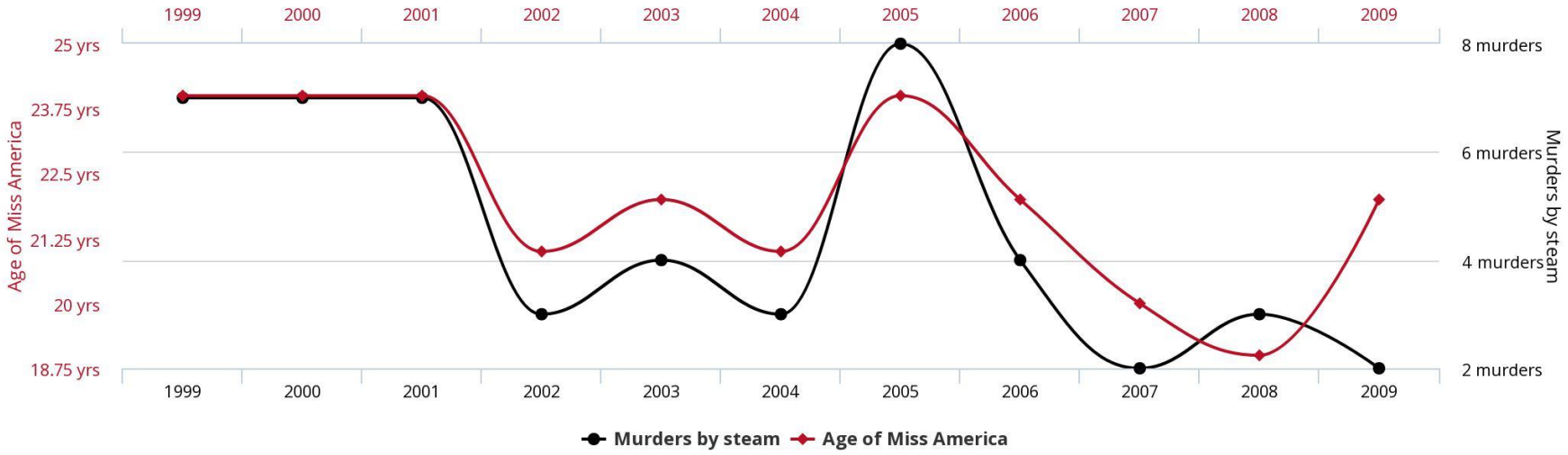


Source: Tyler Vigen's Spurious Correlations Website

Divorce rate in Maine
correlates with
Per capita consumption of margarine



Age of Miss America
correlates with
Murders by steam, hot vapours and hot objects



tylervigen.com

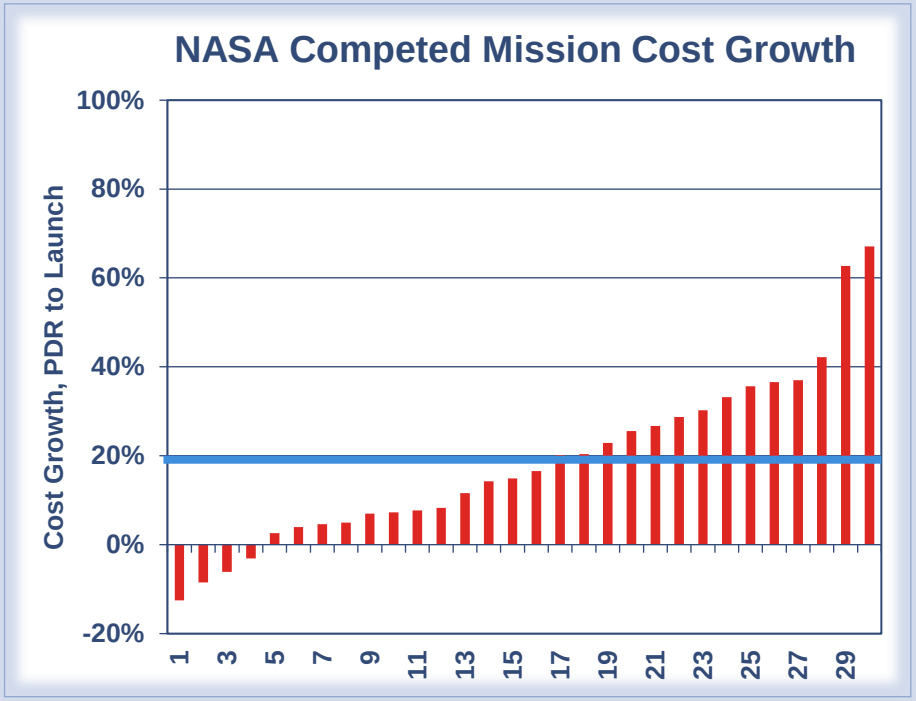
Cost Growth Comparison via T-Test

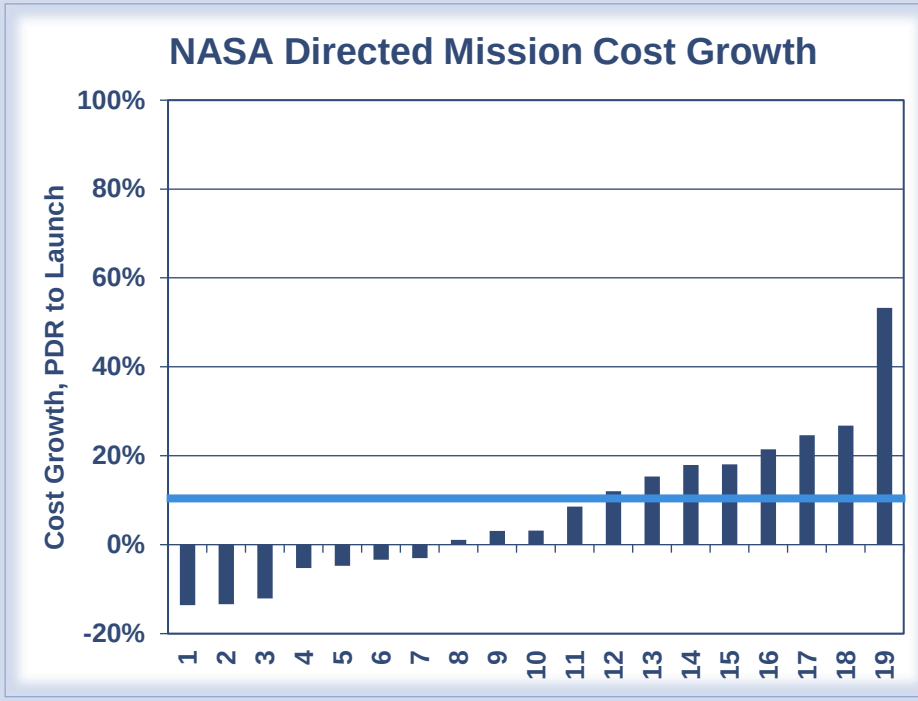
- Performed a t-test to see if the difference between the two means in statistically significant
- H_0: $\mu_{competed} = \mu_{directed}$
- H_1: $\mu_{competed} > \mu_{directed}$

T Test Summary (Two-sample t-test assuming unequal variances with a α of 0.05)			
	Variable 1: Competed	**Variable 2: Directed**	**Notes**
Mean	19%	8%	Average cost growth of competed versus directed missions
Variance	0.04	0.03	Similar variability
Observations	30	19	Number of missions in each dataset respectively
Hypothesized Mean Difference	0.00		Null hypothesis (as seen above)
df	42.00		Degrees of freedom for t-test
t Stat	2.08		Variable 1 is 2.1 standard deviations away from Variable 2
P(T<=t) one-tail	0.02		P-value is less than 0.05

- The difference is statistically significant
  - Competed NASA missions have experienced more cost growth than directed NASA missions

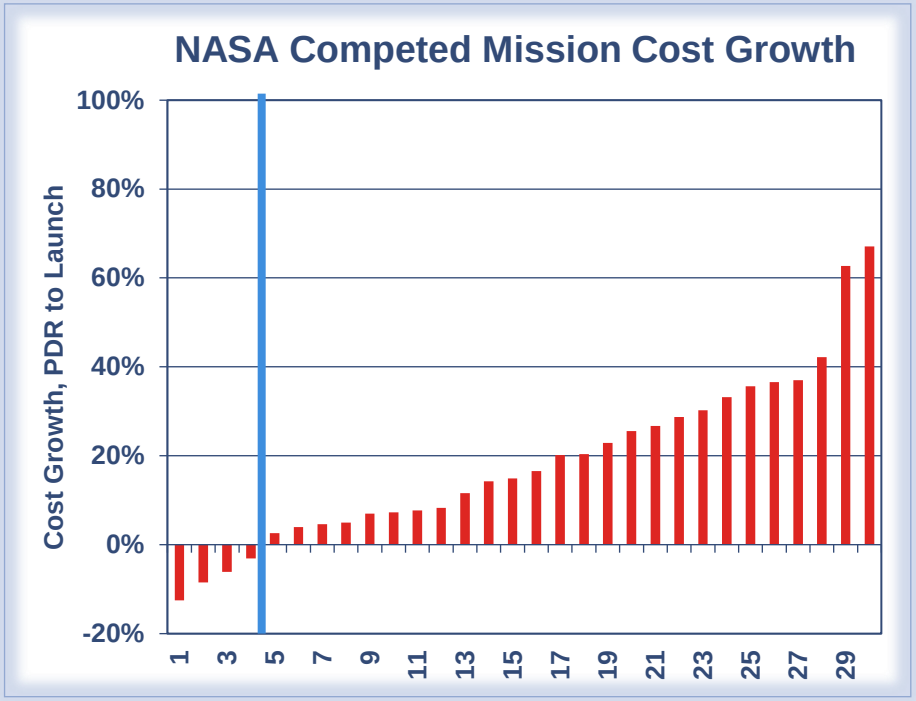
Competed vs Directed Cost Growth

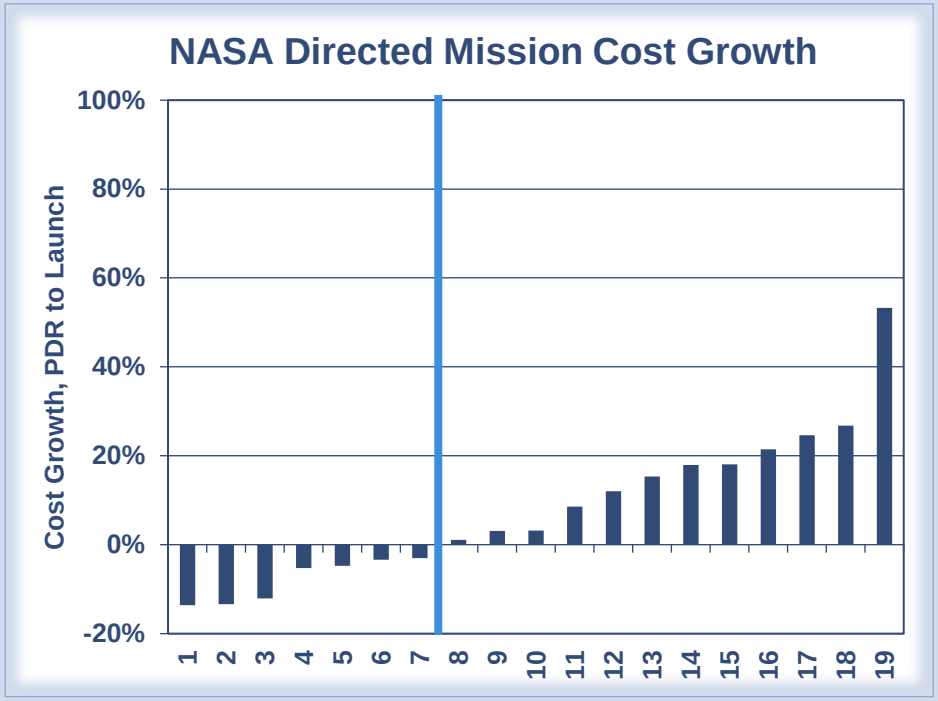




Acquisition Strategy	Average Cost Growth
Competed	19%
Directed	8%

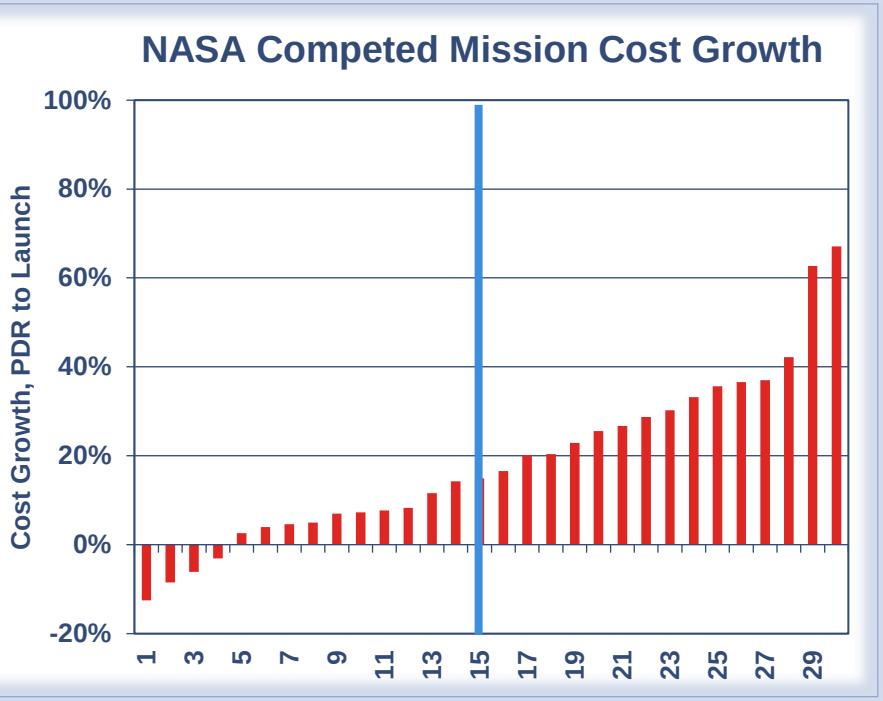
Competed vs Directed Cost Growth

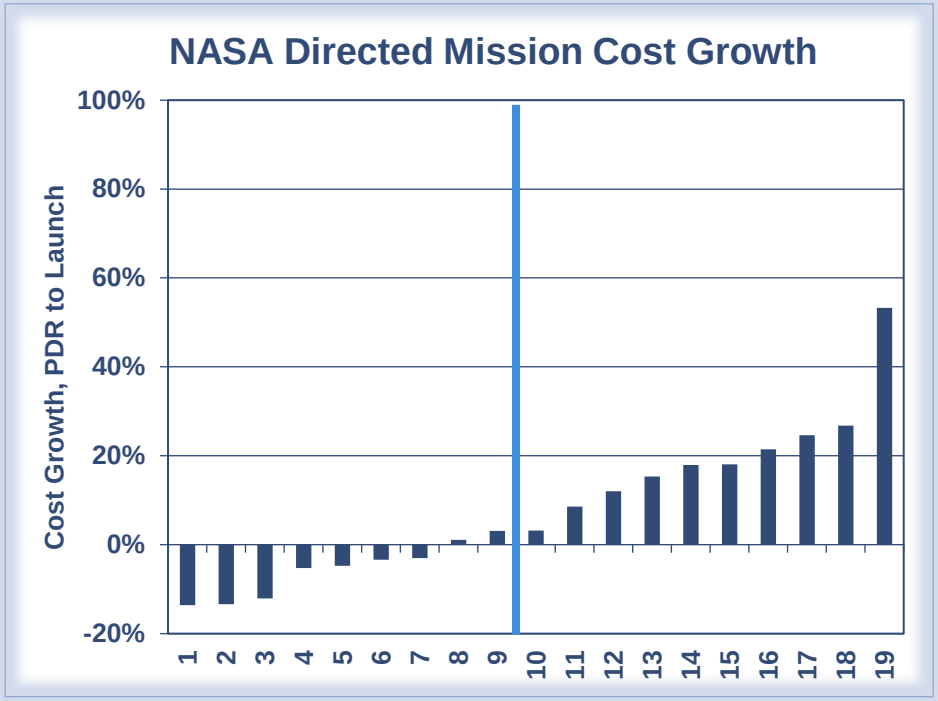




- 87% of competed missions experienced cost growth
- 63% of directed missions experienced cost growth

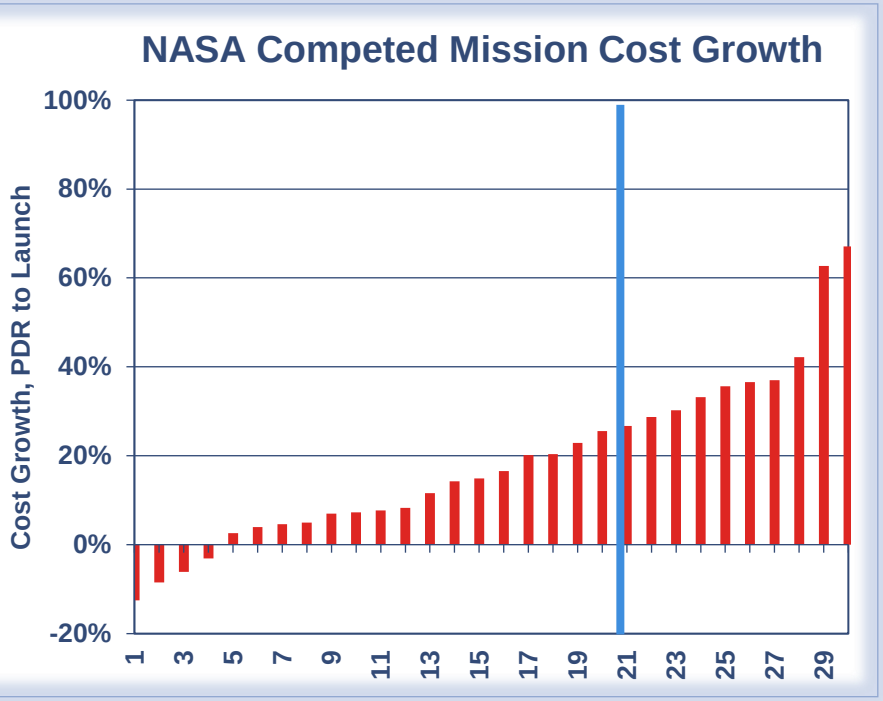
Competed vs Directed Cost Growth

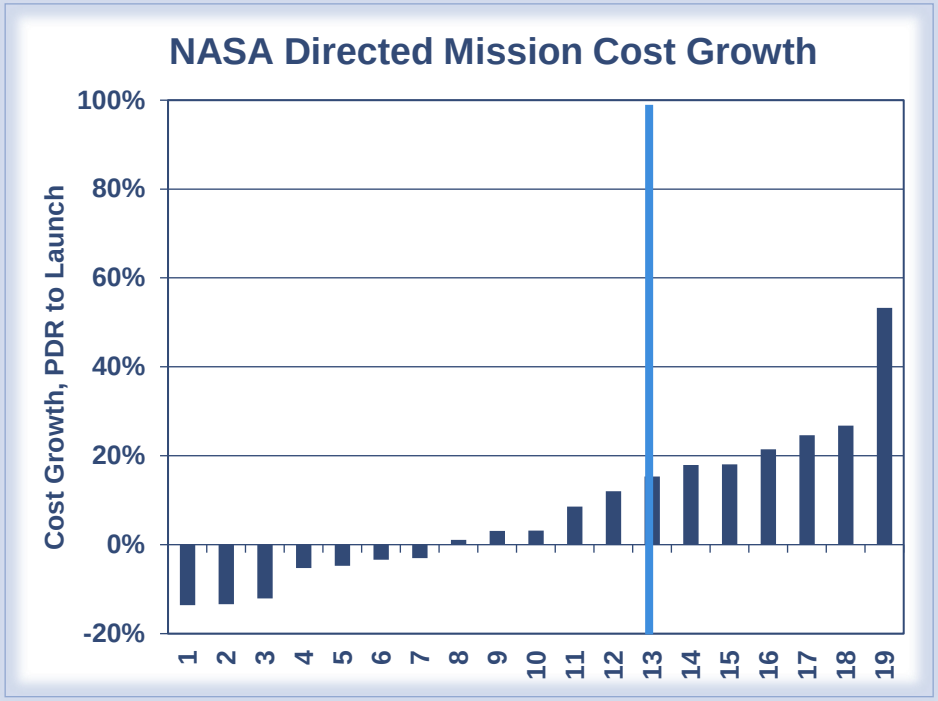




- At the empirical 50th percentile of competed missions, cost growth is 15% in addition to project-held UFE
- At the empirical 50th percentile of directed missions, cost growth is 3% in addition to project-held UFE

Competed vs Directed Cost Growth





- At the empirical 70th percentile of competed missions, cost growth is 27% in addition to project-held UFE
- At the empirical 70th percentile of directed missions, cost growth is 15% in addition to project-held UFE

What This Really Means…

- Given the available data set, the difference between the average cost growth of competed versus directed missions is significant
- We also know there is a difference in the percentage of competed missions that experienced cost growth compared to a directed mission

WHY?

- Are more resources available early in the formulation process for directed missions to generate robust cost estimates than for proposals/competed missions?
- Are we overly optimistic when we generate cost estimates and risk analyses for competed missions?
- Are we setting overly ambitious science goals for competed missions in each of the program lines?

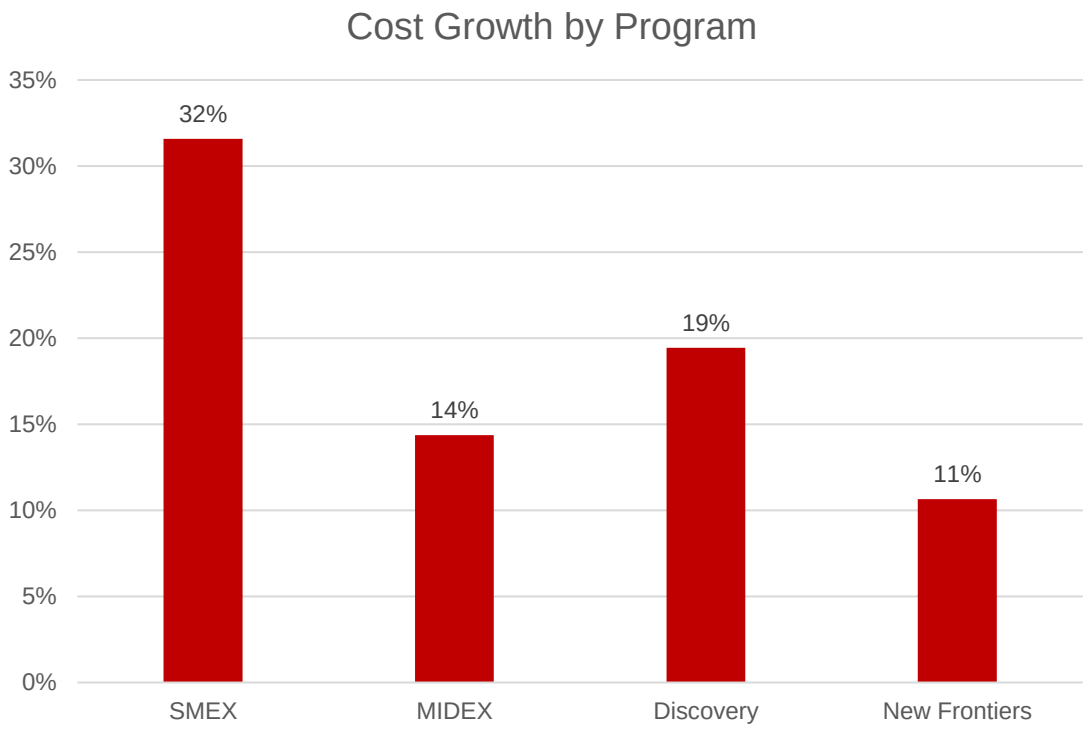
Cost Growth by Program Line

- Looked at average cost growth by program line of competed missions
- Performed t-tests to see if there is a difference between one program and the missions not in that program

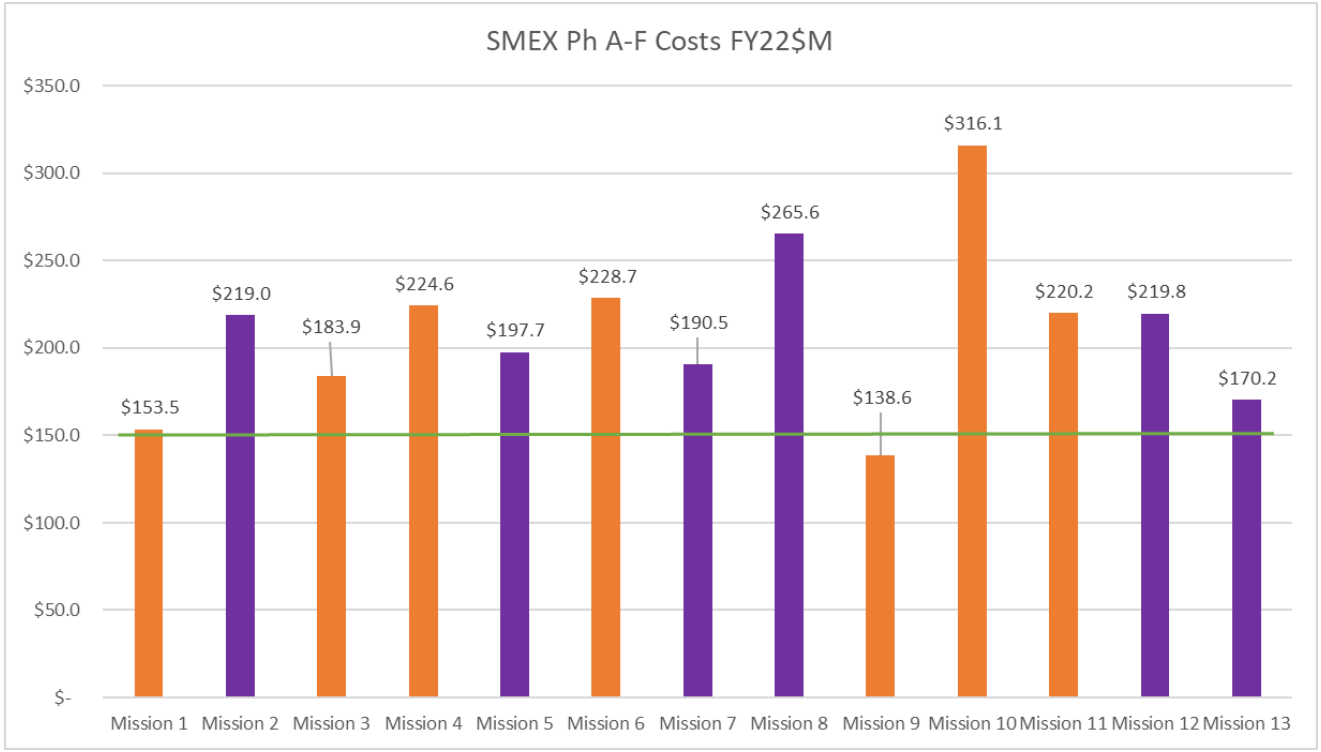
Program Line	Average Cost Growth
SMEX	32%
Non-SMEX	16%

SMEX vs. Non-SMEX T Test Summary	
T statistic	3.07
P value	<0.01

- SMEX vs non-SMEX is statistically significant
- → The program line with the lowest cost cap experiences the most cost growth

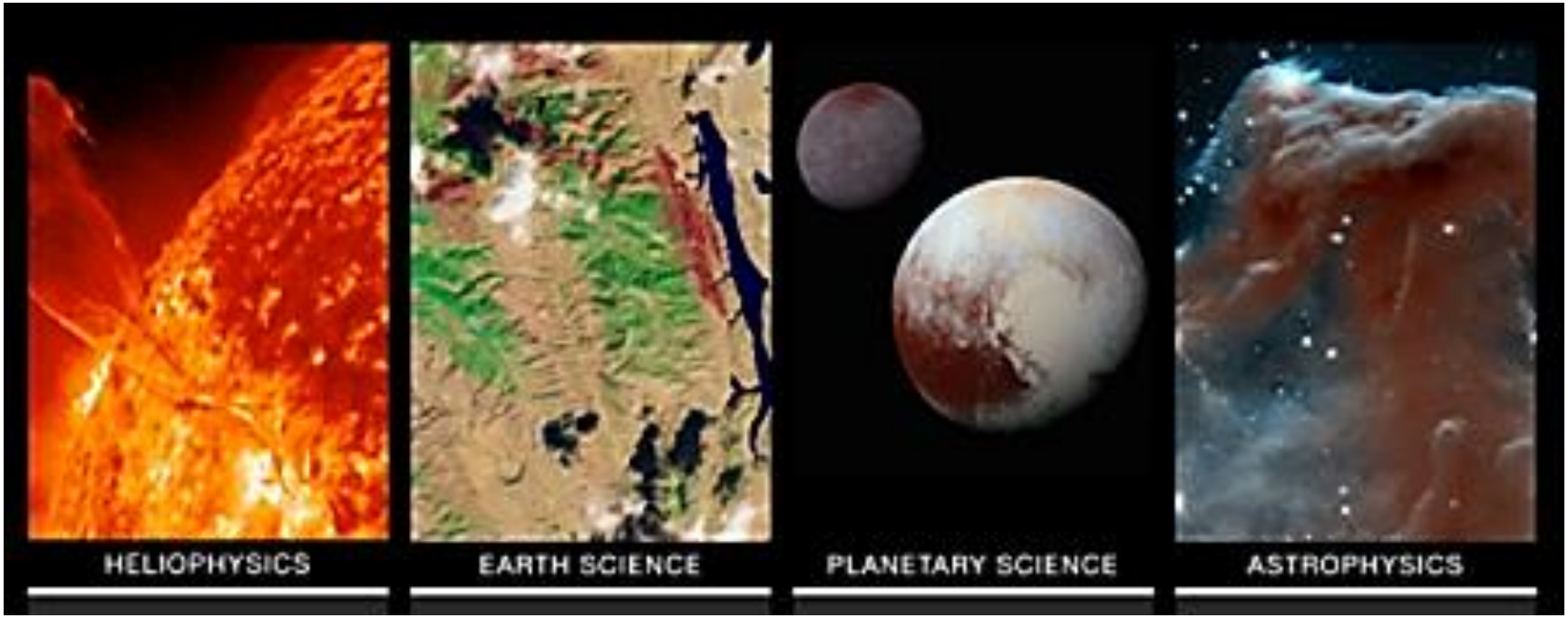


SMEX Cost Cap



- Kathy Kha's 2022 NCSS Presentation "*Tipping Our Caps: How Well Does SMEX Fit into its Cost Cap?*" dove into this

Science Mission Directorate Divisions



- Is there any relationship between SMD division and cost growth for competed and directed missions?

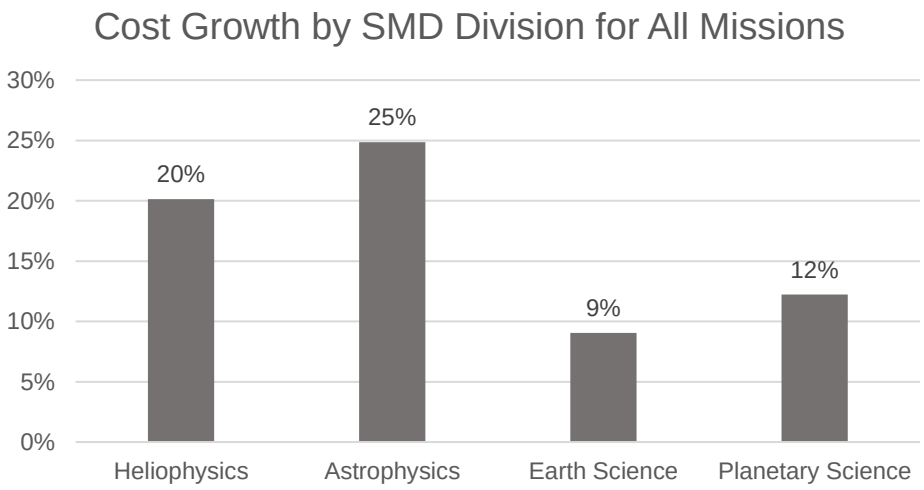
Cost Growth by SMD Division

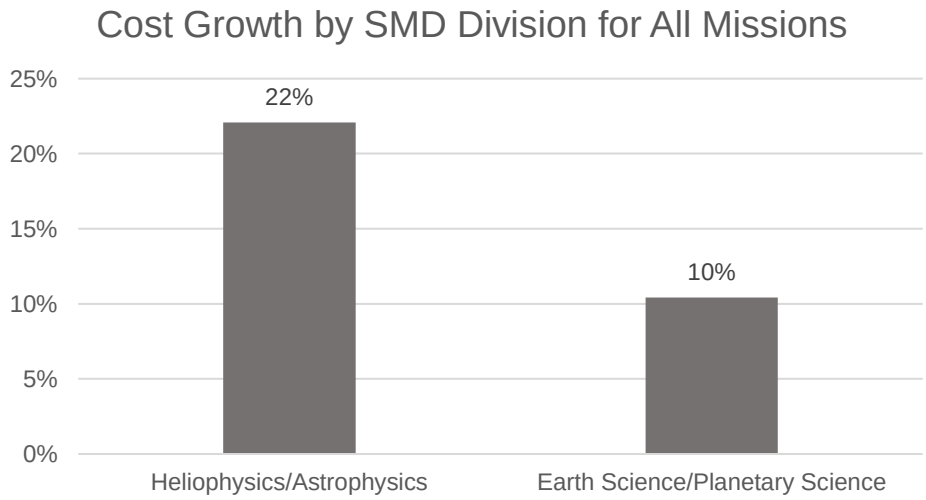
- Observed a visual difference between Heliophysics/Astrophysics and Earth/Planetary science

SMD Division	Average Cost Growth
Heliophysics/Astrophysics	22%
Earth/Planetary Science	10%

T Test Summary	
T statistic	2.39
P value	0.01

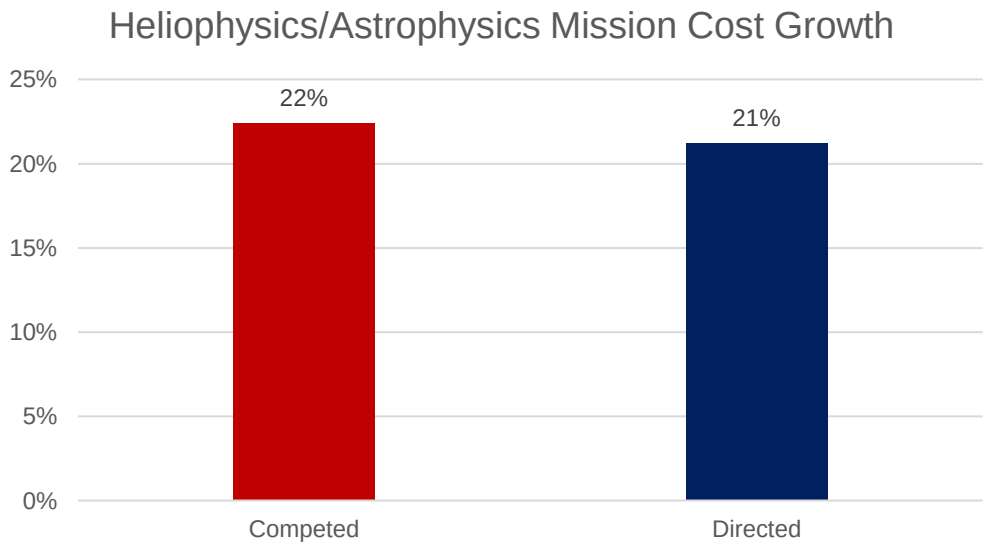
- Performed a t-test to see if there is a difference between the two groups
- Heliophysics/Astrophysics vs Earth Science/Planetary Science is statistically significant
  - Are SMEX missions are driving the Heliophysics/Astrophysics averages?





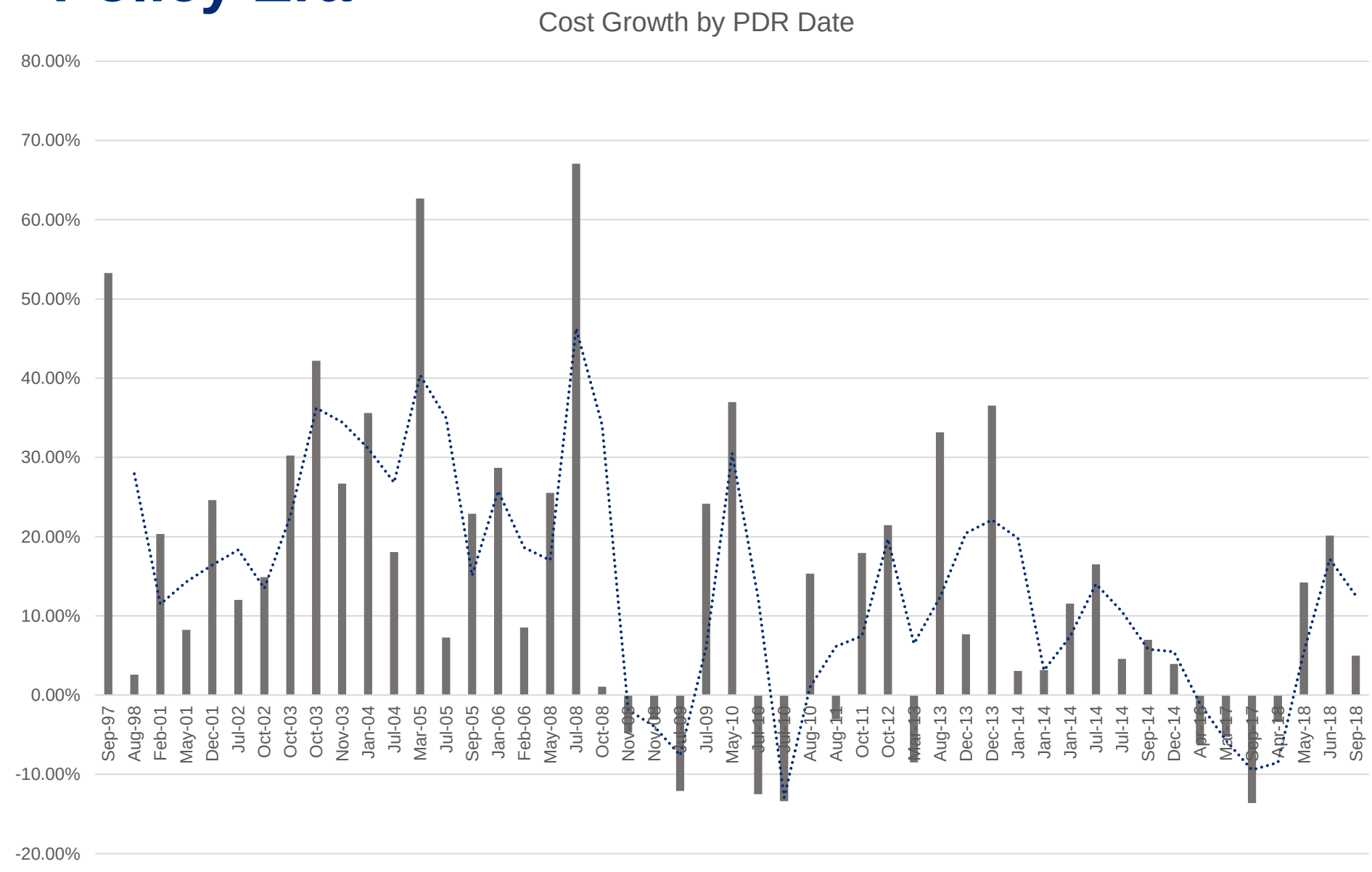
This dataset does not include Astrophysics and Planetary Science missions over $1B.

Heliophysics/Astrophysics Cost Growth



- While SMEX missions might be driving the Heliophysics/Astrophysics competed average, the average for directed Heliophysics/Astrophysics missions is almost the same

Policy Era


Cost Growth by PDR Date
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
-10.00%
-20.00%
Sep-97
Aug-98
Feb-01
May-01
Dec-01
Jul-02
Oct-02
Oct-03
Oct-03
Nov-03
Jan-04
Jul-04
Mar-05
Jul-05
Sep-05
Jan-06
Feb-06
May-08
Jul-08
Oct-08
Jul-09
May-10
Aug-10
Aug-11
Oct-11
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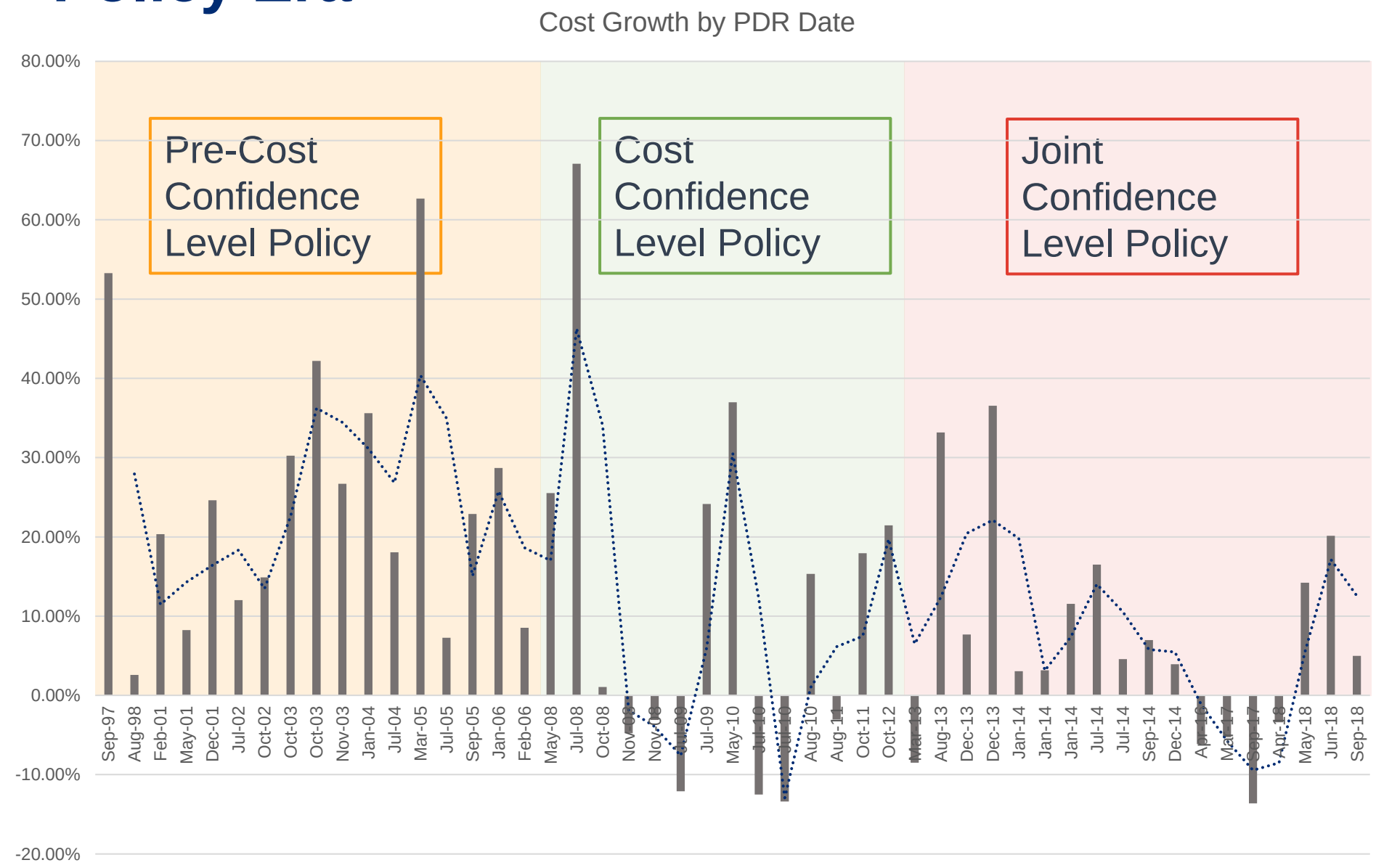
Dec-13
Dec-13
Jan-14
Jan-14
Jan-14
Jul-14
Jul-14
Sep-14
Dec-14
May-18
Jun-18
Sep-18

Policy Era


Cost Growth by PDR Date
Pre-Cost Confidence Level Policy
Cost Confidence Level Policy
Joint Confidence Level Policy
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
-10.00%
-20.00%
Sep-97
Aug-98
Feb-01
May-01
Dec-01
Jul-02
Oct-02
Oct-03
Oct-03
Nov-03
Jan-04
Jul-04
Mar-05
Jul-05
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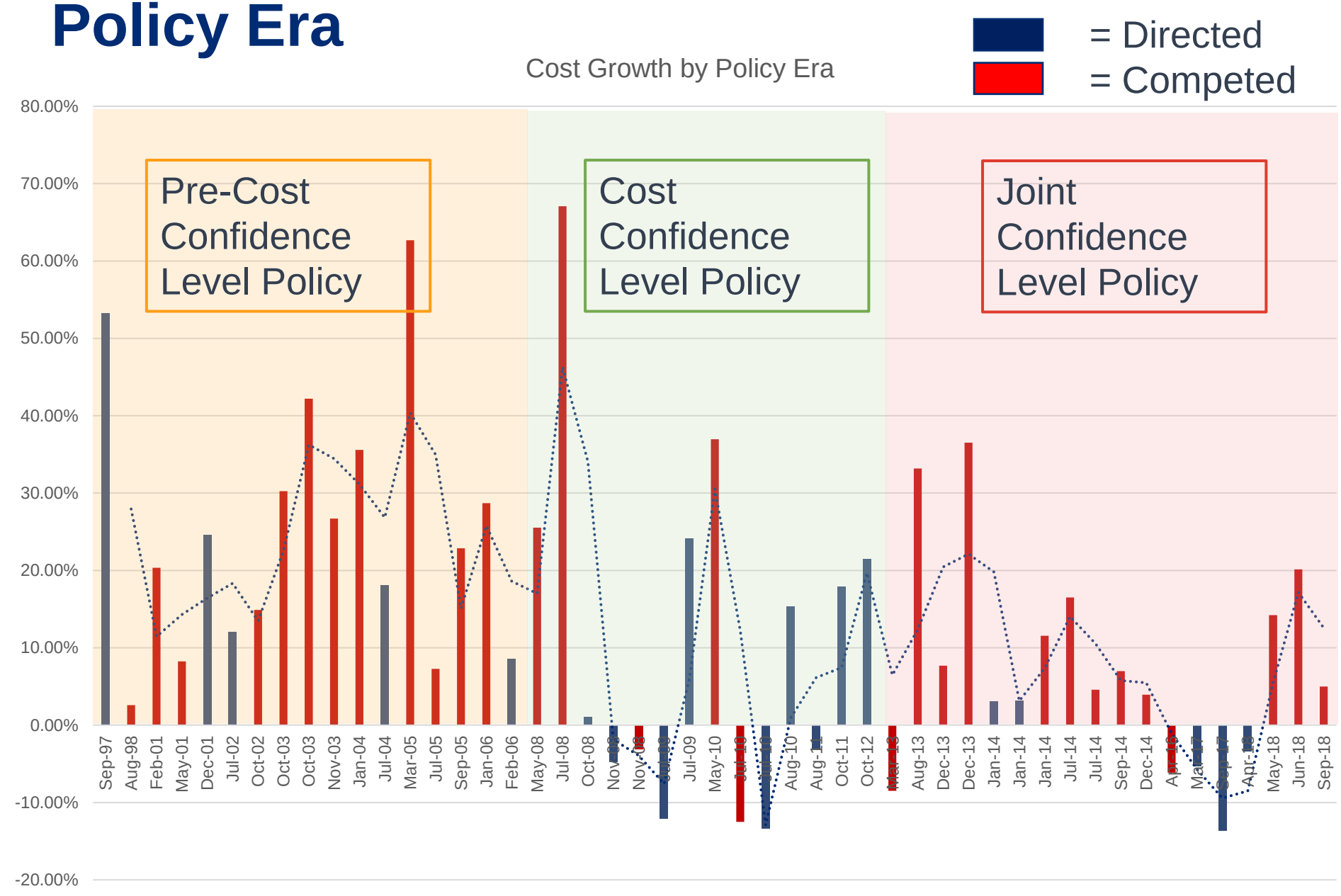
Sep-14
Dec-14
May-18
Jun-18
Sep-18

Policy Era


Cost Growth by Policy Era
= Directed
= Competed
Pre-Cost Confidence Level Policy
Cost Confidence Level Policy
Joint Confidence Level Policy
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
-10.00%
-20.00%
Sep-97
Aug-98
Feb-01
May-01
Dec-01
Jul-02
Oct-02
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Jan-04
Jul-04
Mar-05
Jul-05
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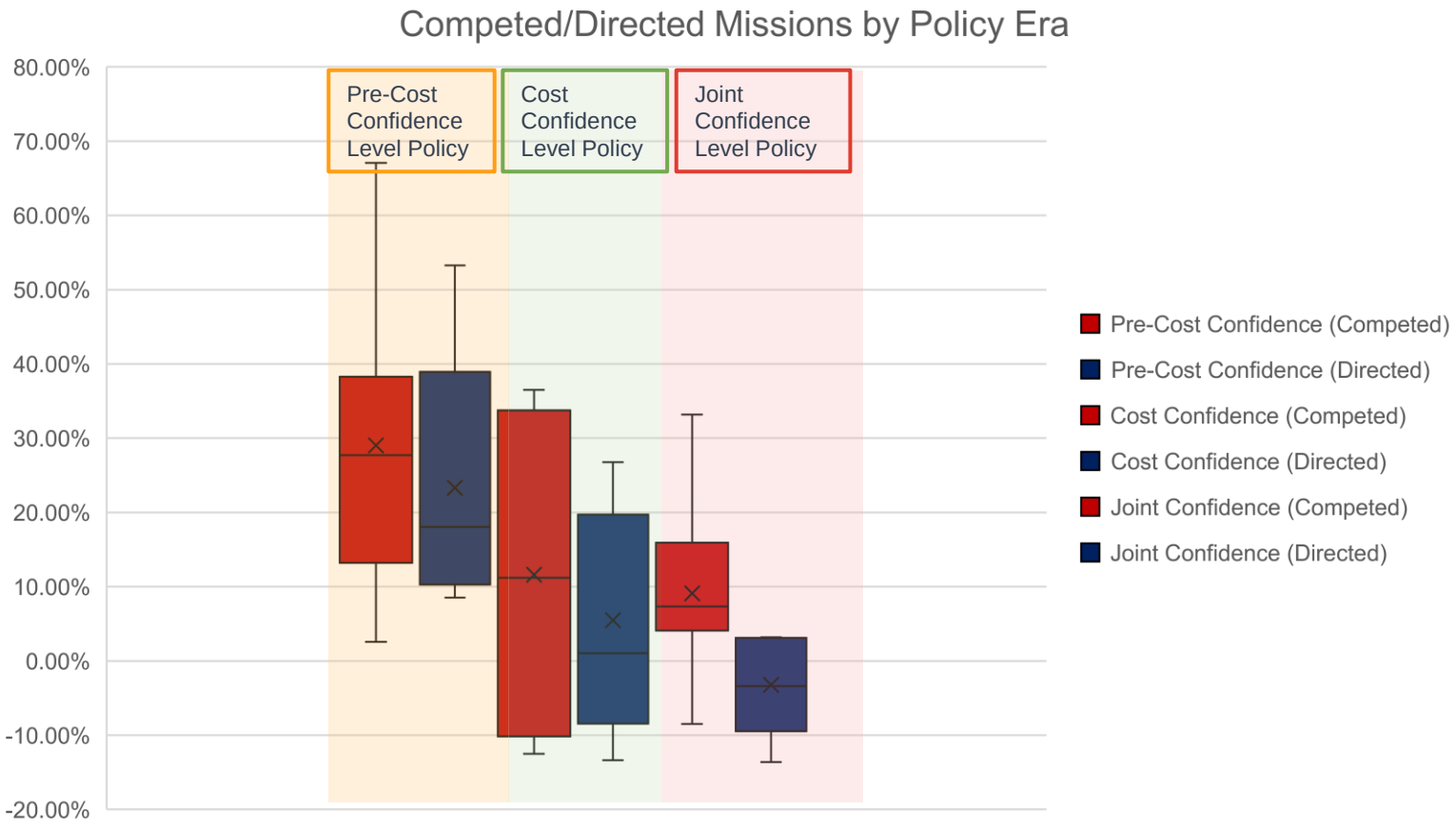
Policy Era



Average Cost Growth	Pre-Cost Confidence	Cost Confidence	Joint Confidence
Competed	29%	12%	9%
Directed	23%	5%	-3%

Policy Era Findings

Average Cost Growth	Pre-Cost Confidence	Cost Confidence	Joint Confidence
Competed	29%	12%	9%
Directed	23%	5%	-3%

- Ran an ANOVA test to see if there is a statistically significant difference between the means of the three policy eras for competed and directed missions

ANOVA Summary	
F Statistic	4.68
P value	<0.01

- The results are statistically significant supporting the assertion that new programmatic requirements help NASA control costs
- A deeper dive into which pairs are significant will be done in the future

Correlation

	Cost Growth	*Acquisition Strategy*	*Program Line*	*SMD Division*	*Policy Era*
Cost Growth	100%				
Acquisition Strategy	29%	100%			
Program Line	31%	27%	100%		
SMD Division	30%	14%	46%	100%	
Policy Era	51%	4%	14%	7%	100%

Correlation

	Cost Growth	*Acquisition Strategy*	*Program Line*	*SMD Division*	*Policy Era*	*Implementing Organization*
Cost Growth	100%					
Acquisition Strategy	29%	100%				
Program Line	31%	27%	100%			
SMD Division	30%	14%	46%	100%		
Policy Era	51%	4%	14%	7%	100%	
Implementing Organization	50%	25%	-2%	-4%	44%	100%

Correlation

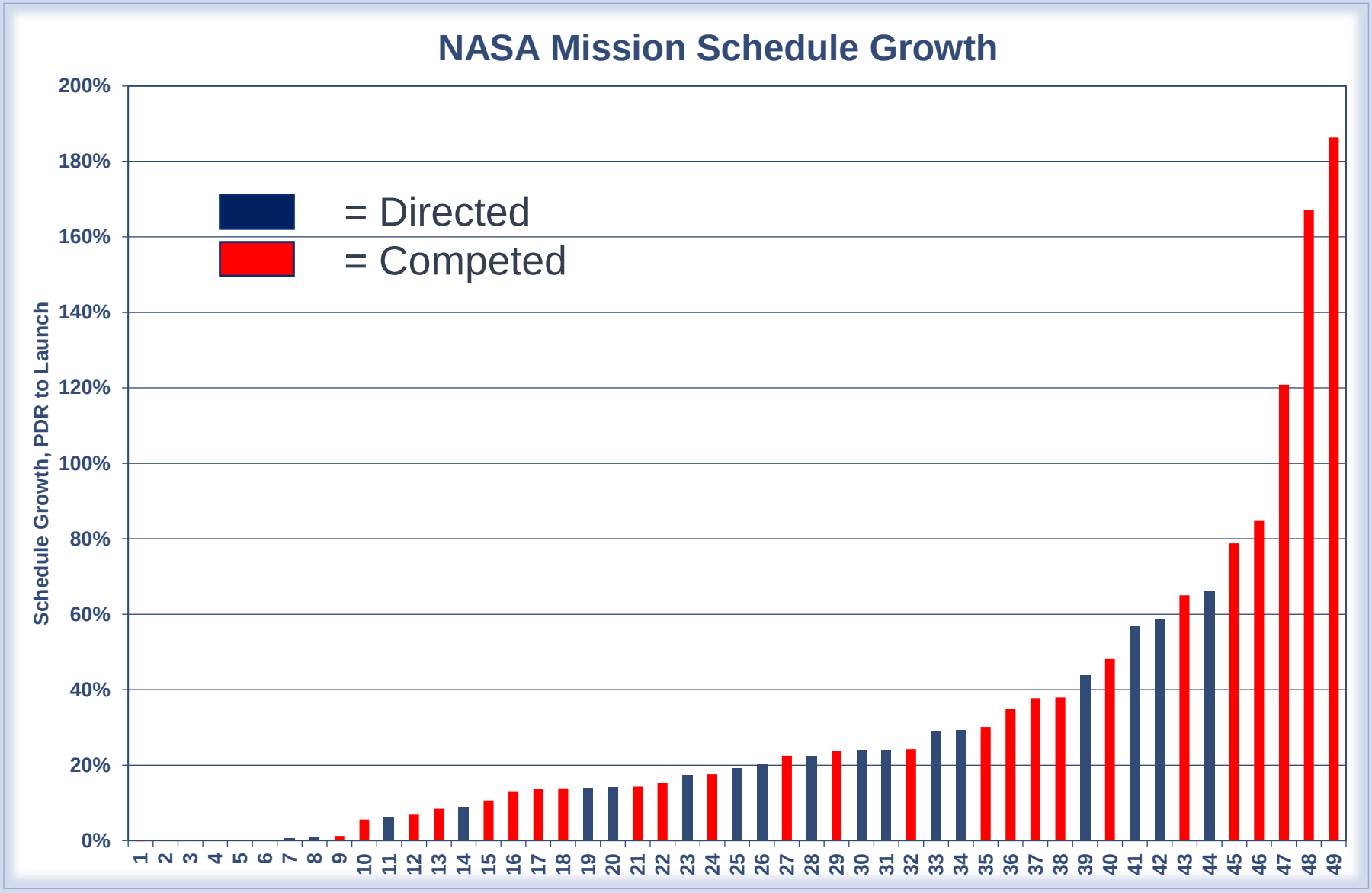
	Cost Growth	*Acquisition Strategy*	*Program Line*	*SMD Division*	*Policy Era*	*Implementing Organization*
Cost Growth	100%					
Acquisition Strategy	29%	100%				
Program Line	31%	27%	100%			
SMD Division	30%	14%	46%	100%		
Policy Era	51%	4%	14%	7%	100%	
Implementing Organization	50%	25%	-2%	-4%	44%	100%

- Implementing Organization and Policy Era
- Implementing Organization and Acquisition Strategy

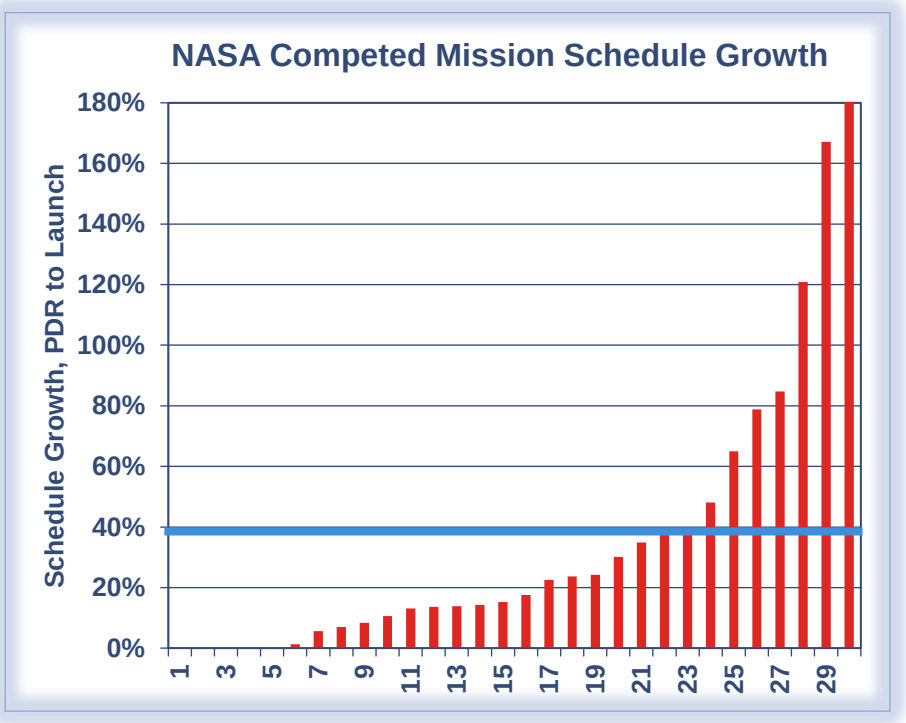
Methodology: Data Collection & Normalization

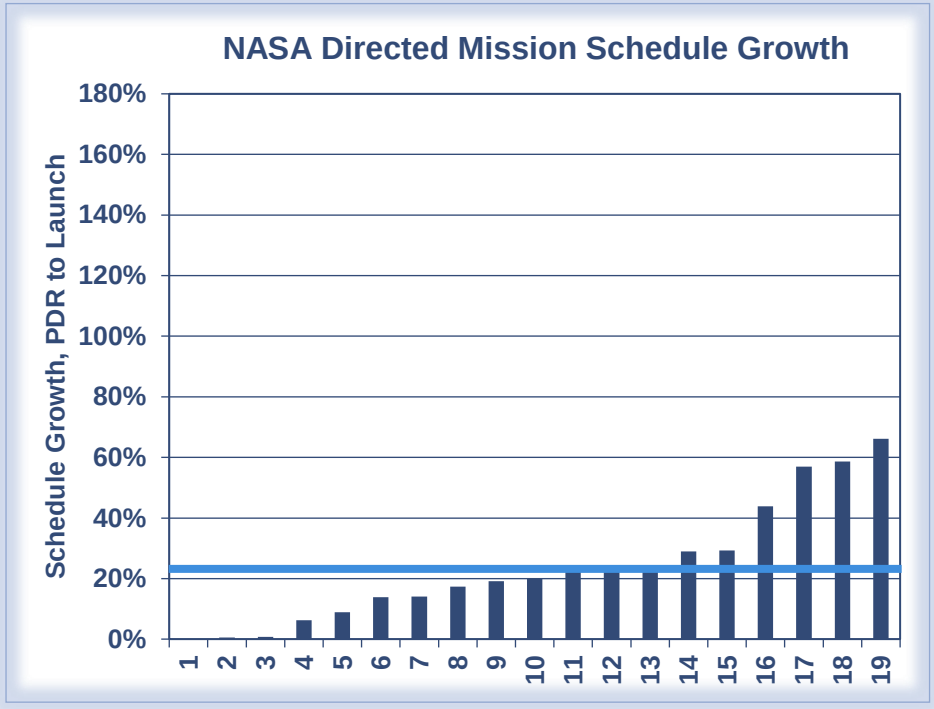
- Schedule data collected via PDR and Launch CADRes (Part C)
- Looked at the same 49 missions (30 competed and 19 directed)
- Schedule growth was calculated from PDR to Launch as:
  - $schedule\ growth = \frac{(PDR\ to\ Actual\ Launch\ Duration - PDR\ to\ Predicted\ Launch\ Duration)}{PDR\ to\ Predicted\ Launch\ Duration}\ x\ 100\%$

Competed versus Directed Missions



Competed vs Directed Schedule Growth





Competed Mission Summary Statistics	
Mean	36%
Median	16%
Standard Deviation	0.48
Minimum	0%
Maximum	186%

Directed Mission Summary Statistics	
Mean	24%
Median	20%
Standard Deviation	0.20
Minimum	0%
Maximum	66%

Schedule Growth Comparison via T-Test

- Performed a t-test to see if the difference between the two means in statistically significant
- H_0: $\mu_{competed} = \mu_{directed}$
- H_1: $\mu_{competed} > \mu_{directed}$

T Test Summary (Two-sample t-test assuming unequal variances with a α of 0.05)			
	Variable 1: Competed	**Variable 2: Directed**	**Notes**
Mean	36%	24%	Average schedule growth of competed versus directed missions
Variance	0.23	0.04	Variability of competed missions is much larger than directed missions
Observations	33	17	Number of missions in each dataset respectively
Hypothesized Mean Difference	0.00		Null hypothesis (as seen above)
df	42.00		Degrees of freedom for t-test
t Stat	1.23		Variable 1 is 1.2 standard deviations away from Variable 2
P(T<=t) one-tail	0.11		P-value is not less than 0.05

- The difference is not statistically significant. As new data points become available, this should be continually monitored.

This dataset parallels the cost dataset. If outliers are removed, the averages are 23% vs 17%, respectively, and the p-value is 0.16.

Conclusions

- In this dataset, there is a clear difference in cost growth between competed and directed missions
- We also know there is a difference in the percentage of competed missions that experienced cost growth compared to directed missions
- This study is focused on observed cost growth between competed and directed missions without taking any causality into account
- This study excludes missions over $1B. While the inclusion of these astrophysics and planetary science flagship missions might alter the findings, it is important to examine cost growth of missions under $1B since the majority of NASA missions fall below this threshold
- One of the ways the community can help is to treat every cost estimate with a high level of rigor and skepticism, devote the right resources to get the details worked out, and approach risk and uncertainty with candor

Suggestions for Future Research

- Analyze cost growth prior to PDR
- Analyze cost growth by SMD divisions more in depth
- Analyze cost growth by implementing organization more in depth
- Analyze complexity of missions and relation to cost growth
- Analyze cost growth by WBS
- Analyze cost growth of operations and phase E costs
- Analyze cost growth of flagship missions
- Analyze schedule growth more in depth and how it compares to cost growth
- Analyze cost growth using other sources
- Analyze correlation among all of the factors more in depth and create a multiple linear regression model

JOHNS HOPKINS

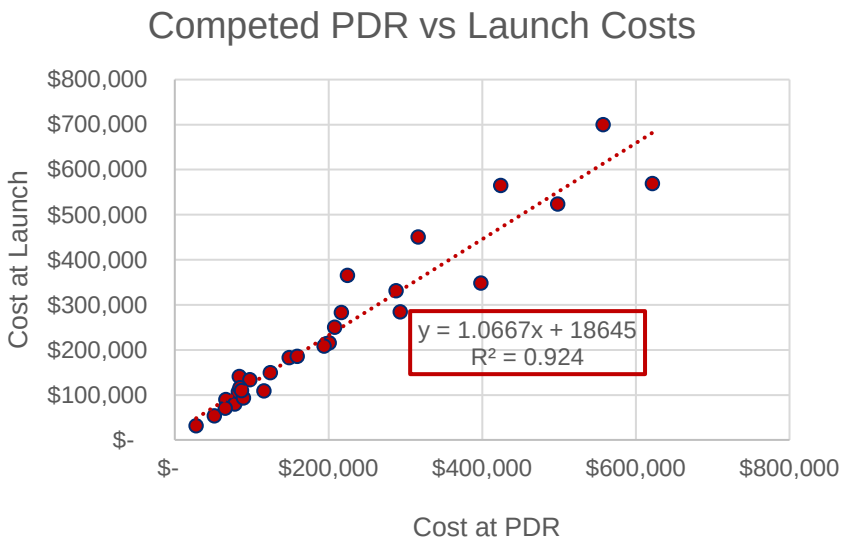
APPLIED PHYSICS LABORATORY

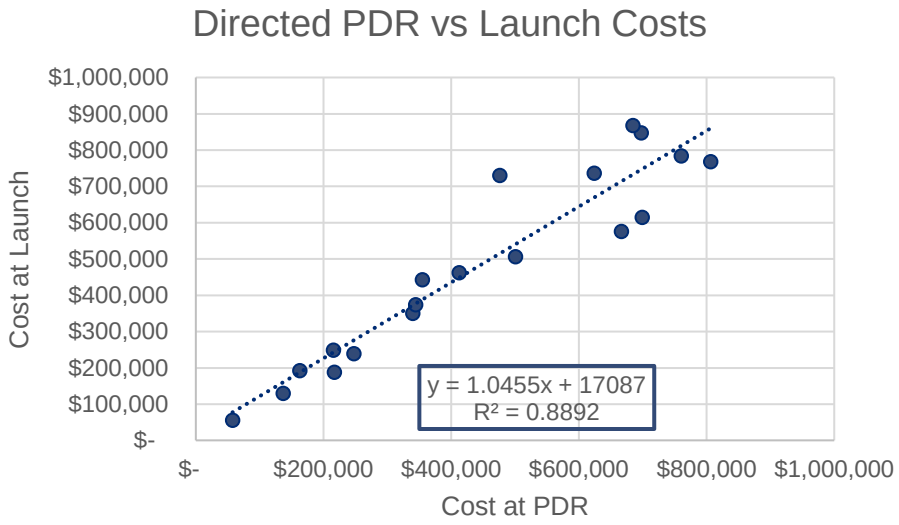
Backup

Missions in Dataset

Missions				
AIM	GRACE	JUNO	MRO	SMAP
Aquarius	GRACE-FO	KEPLER	New Horizons	Spitzer
CLOUDSAT	GRAIL	LADEE	NICER	STEREO
CYGNSS	IBEX	Landsat 9	NuSTAR	TEMPO
DART	ICESAT-2	LDCM	OCO	TESS
DAWN	ICON	LRO	OCO2	THEMIS
DEEP IMPACT	InSight	Lucy	OSIRIS-REx	TROPICS
GEDI	IRIS	MAVEN	Parker Solar Probe	Van Allen Probes
GOLD	IXPE	MESSENGER	Phoenix	WISE
GPM	JASON 3	MMS	Sentinel-6	

Predicted Cost Growth of Competed vs Directed Missions





- Average prediction error 6%
- Predictor error standard deviation of 0.19

- Average prediction error 5%
- Predictor error standard deviation of 0.17

Correlation of Cost and Schedule

- Correlation of cost and schedule growth was evaluated for all missions, for competed missions only, and for directed missions only
- For directed missions, cost and schedule growth is correlated at almost 0.1
- For competed missions, cost and schedule growth is correlated ~0.2

All Missions	*Cost Growth*	*Schedule Growth*
Cost Growth	1	
Schedule Growth	0.21	1

Directed Missions	*Cost Growth*	*Schedule Growth*
Cost Growth	1	
Schedule Growth	0.08	1

Competed Missions	*Cost Growth*	*Schedule Growth*
Cost Growth	1	
Schedule Growth	0.22	1

Correlation of Cost and Schedule