The Class-D Conundrum: Quantifying Cost Efficiencies for Lower-Class Missions

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Agenda

- Background / Key Questions
- Research Methodology
- Class-D Hardware Actual vs. Modeled Costs
- Calibrations for Future Class-D Hardware Estimates
- Class-D Wrap-Factors (PM/SE/MA)
- Conclusions/Future Research

Background

- In a budget-constrained environment, there are more opportunities for lower cost missions
  - Discovery, New Frontiers, Flagship opportunities fewer and farther between
  - Critical to develop missions within a constrained cost cap (e.g. <$250M)
- Concurrently, NASA remains risk averse
  - Rapidly changing requirements & “requirements creep”
    - More robust/numerous processes, procedures, documentations, and program reviews
  - All mission classes must demonstrate cost credibility, cost realism, and mission assurance
- Classifying missions as C-/D attempts to reconcile these two issues; however, it is unclear how (if?) Class D translates to tailored/reduced requirements
  - ***Should cost estimates reflect a more aggressive risk posture?***
- Validating proposed costs of Class D missions is problematic:
  - Primary cost databases constructed of missions subject to Class A/B/C requirements, higher complexity, larger lifetimes, and larger payload *suites*— ***independent estimates are biased high as a result***
  - Challenging to validate costs for missions that, by definition, should be more accepting of cost, schedule, and technical risk

Background, Continued

- Not all "Class D" missions are created equal
  - Risk tolerance varies by mission; requirements tailoring not well defined
- Balloon Missions of particular interest
  - Unique opportunities for low-cost science return
  - Balloon gondola/payload data not available in NASA cost databases for proposal cost validation/CERs
  - Standard modeling tools considerably overestimate cost
  - Parametric modeling difficult for evaluators
  - Class "D-"
- Class D Spacecraft, should, theoretically, demonstrate cost savings:
  - Hardware/design reuse where possible
  - Reduced testing/oversight
  - Shorter mission lifetime (single string, reduced reliability)
- NASA 7120.5E does not specify mission class
  - Projects must assume they are subject to all requirements without specific waivers
  - How is this reflected in project PM/SE/MA costs, and how do we estimate them for Class D going forward?
- Limited supporting data available industry wide

Key Questions:

- Are there quantifiable hardware cost efficiencies associated with Class D missions?
- How can we adjust spacecraft cost models in a data-driven manner to accurately estimate these missions going forward?
- Does Class-D classification have a noticeable impact on mission wrap costs PM/SE/MA given consistency in 7120 requirements?

Methodology: Overview

- Identified Class D(ish) missions with sufficient cost/technical data for analysis of spacecraft and PM/SE/MA costs
  - Cost and technical data at the spacecraft subsystem level
- For hardware analysis, we modeled each mission using PRICE and SSCM and compared estimates with realized costs at the total spacecraft level and at the subsystem level (Detailed methodology on following slide)
  - Efficiencies may be more pronounced for particular subsystems
  - Quantifies cost impact of complexity/class independent of mass
  - Detailed hardware calibration of realized mission costs can be used as a means of estimating Class D going forward
- We compared PM/SE/MA costs as percentage of the flight system to Class A/B/C missions
  - Previous analysis demonstrates that hardware remains an accurate predictor of wrap-costs

Methodology: Data Collection & Normalization

- CADRe as primary data source, with some internal APL data
  - Balloon Missions: APL BRRISON and BOPPS (Launched 2013, 2014 respectively)
    - BRRISON and BOPPS data normalized generate a representative gondola cost that does *not* include hardware reuse
  - Spacecraft: GALEX, NuSTAR, OCO, and LADEE
    - Spacecraft referred to as Missions 1-4 (in no particular order) to protect the innocent
  - CADRe Parts A and B for technical and programmatic data; Part C for cost data
  - Limited data points for analysis
- All costs inflated to $FY15 using NASA New Start Inflation Index
- PMSEMA analyzed both as ***mission level*** PMSEMA (WBS 01,02,03) AND ***total*** PMSEMA (WBS 01, 02, 03 plus spacecraft PMSEMA in WBS 06)
- Spacecraft cost defined as hardware only—excludes PMSEMA carried inside of WBS06

Methodology: Spacecraft Hardware

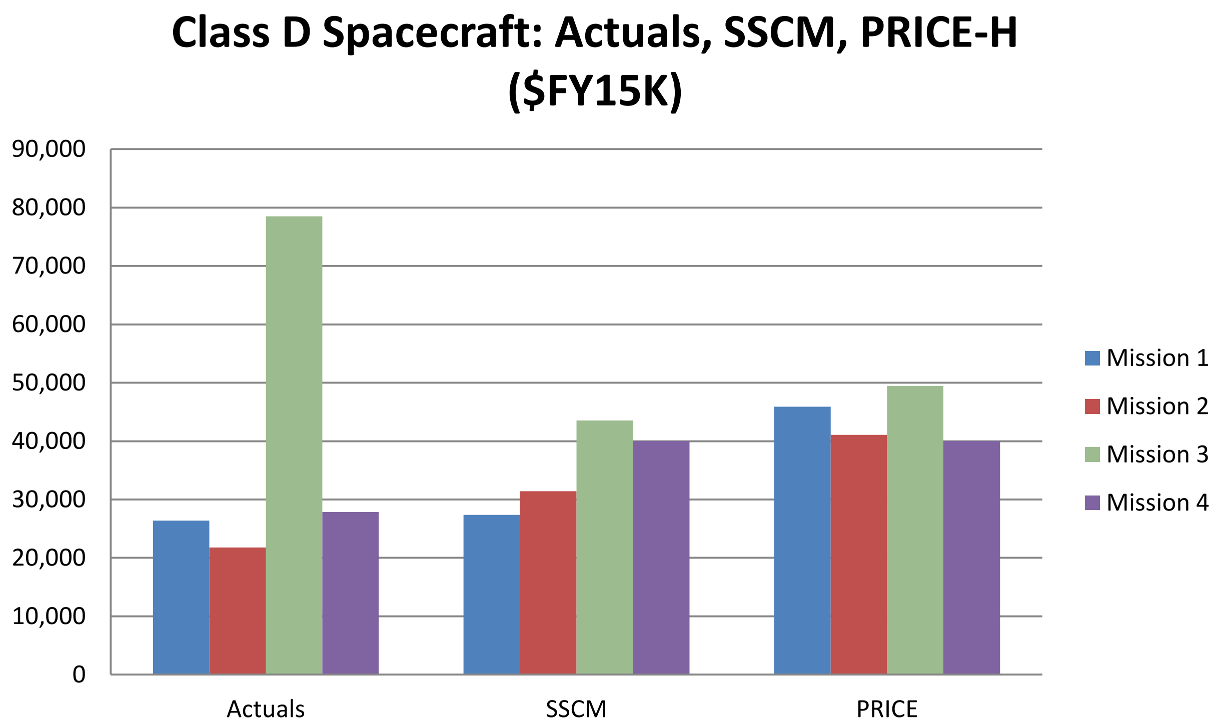
- Modeling hardware in PRICE-H
  - PRICE-H and PRICE TruePlanning are highly sensitive to the manufacturing complexity variable, which is the input that can be calibrated to historical data
  - PRICE Systems conducted research using the NAFCOM database to generate complexity values for spacecraft hardware (at the component and subsystem level; multiple data points for each)
  - We analyzed this data to calculate average/representative complexity values at the spacecraft subsystem level
    - Means of estimating expected value of spacecraft subsystems given historical data in available datasets
    - Cross-checked subsystem averages against APL calculated complexity values at the subsystem level to ensure realism (not biased artificially high or low at any subsystem level)

NAFCOM Spacecraft Subsystem Compexity Averages				
	Average		Std. Dev	
Subsystem	MCPLXS	MCPLXE	XS	XE
RF/Comm	8.639	10.818	1.438	1.539
Attitude Control	10.192	10.638	0.328	1.319
Power Subsystem	9.153	10.034	1.097	1.037
Batteries	8.332		0.903	
Structures/Mechanisms	8.473		1.145	
Avionics	8.264	10.772	0.644	0.998
Thermal	8.868		1.142	
Harness	8.332		0.796	

Methodology: Spacecraft Hardware

- Modeling hardware in PRICE-H, Cont'd
  - These average subsystem complexity factors were used as a means of estimating the expected value of spacecraft hardware under nominal operating processes/procedures (e.g. Class B)
  - Mass, quantities, expected new design, etc. gathered from CADRe Parts A&B
    - For class D, as expected, minimal technology development and high-TRL components
    - In general, high TRL and low NRE assumed in estimates to prevent over-calculating mission cost given mission class
  - Estimates at the subsystem (not component level):
    - Data availability (for inputs and comparison)
    - Comparison to actual cost and SSCM estimates
    - Calibration accuracy—more data points for subsystems than components; averages more likely to be representative of a nominal spacecraft subsystem
  - Gondola platform reduced to 1.65 (vs. 1.9 for spacecraft)
- Modeling hardware in SSCM
  - Top-level spacecraft model that requires relatively few inputs
  - Technical inputs from CADRe Parts A&B
  - Estimates increased to include Phase B
    - ~12% of B-D costs, assuming lower NRE/tech development with Class D
    - Gondola estimates not increased for Phase B due to short development schedule
  - No other adjustments made to estimate output

Spacecraft Hardware: Actuals vs. Predicted, Missions 1-4

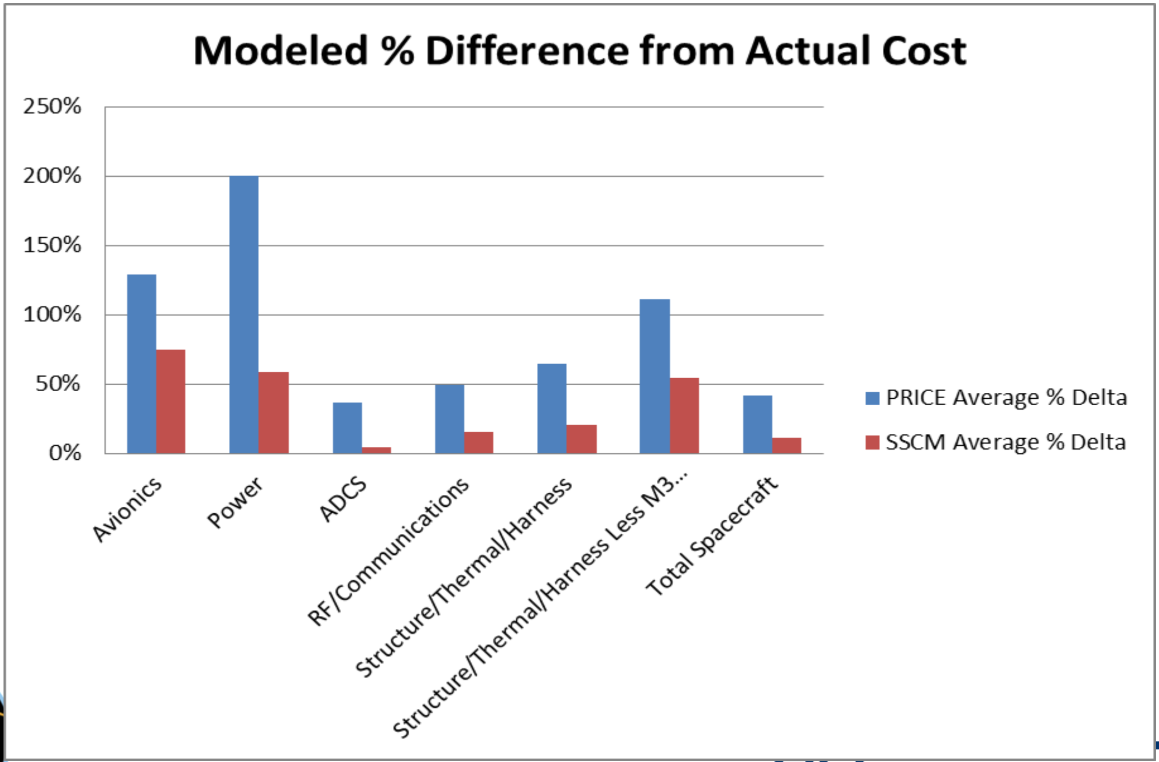


Spacecraft Hardware	Actuals	SSCM	PRICE	PRICE % Delta	SSCM % Delta
Mission 1	$ 26,380.5	$ 27,343.6	$ 45,891.5	74%	3.7%
Mission 2	$ 21,792.8	$ 31,411.2	$ 41,070.4	88%	44.1%
Mission 3	$ 78,475.5	$ 43,519.6	$ 49,465.8	-37%	-44.5%
Mission 4	$ 27,890.6	$ 40,027.7	$ 40,027.7	44%	43.5%
Average				**42%**	**12%**

At the total spacecraft hardware level, PRICE and SSCM overestimated total cost by 42% and 12% *on average*, respectively. This doesn't seem too significant (especially using SSCM), however….

Spacecraft Hardware: Actuals vs. Predicted, Subsystem Details

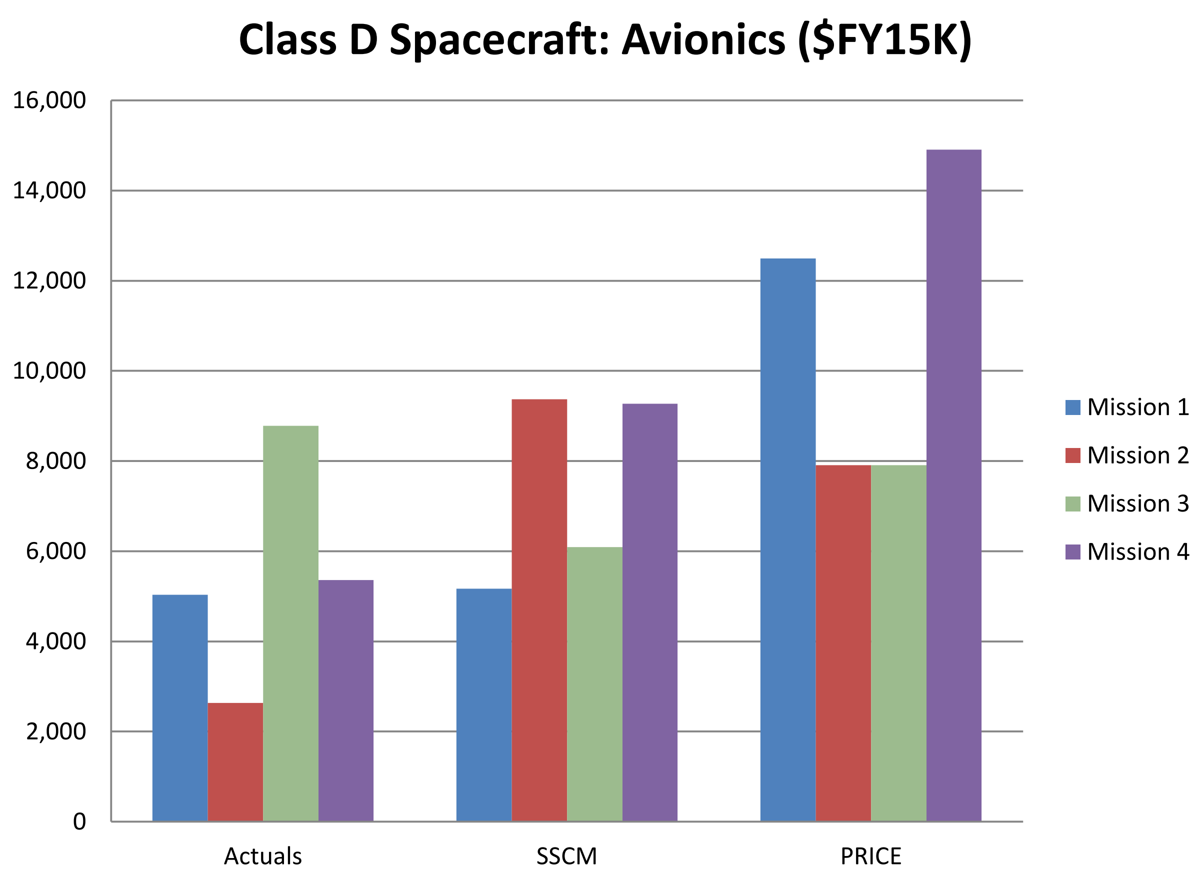
Major Subsystem	PRICE Average % Delta	SSCM Average % Delta
Avionics	129%	75%
Power	200%	59%
ADCS	37%	4%
RF/Communications	50%	15%
Structure/Thermal/Harness	65%	21%
Structure/Thermal/Harness Less M3 Outlier	112%	54%
Total Spacecraft	**42%**	**12%**



There is significant variation at the subsystem level:

- Avionics and Power are grossly overestimated by both SSCM and PRICE
- % difference well outside of the expected error range (+/- 30%)

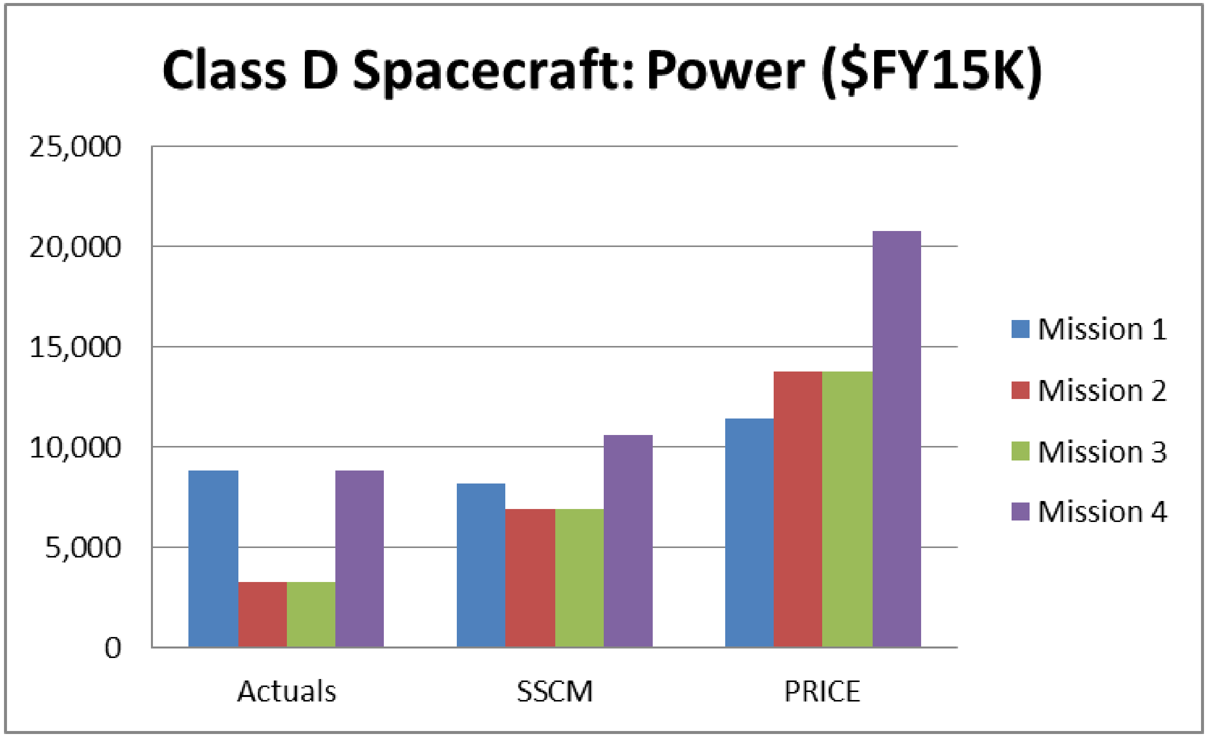
Spacecraft Hardware: Actuals vs. Predicted, Avionics Subsystem



Overestimation of Avionics makes intuitive sense:

- Class-D more likely to use existing architectures/BTP of proven flight designs
- Likely single-string C&DH; less rigorous testing
- Avionics/C&DH tend to be the most costly subsystems, particularly for newer missions with technology development required for data processing
- ***Using traditional modeling techniques may unfairly penalize Class D avionics***
- ***PRICE estimate over by 129%; SSCM 75%***

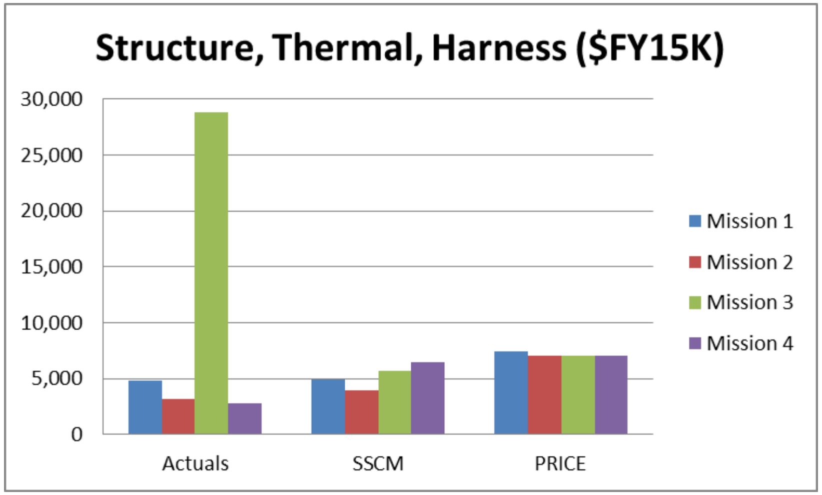
Spacecraft Hardware: Actuals vs. Predicted, Power Subsystem

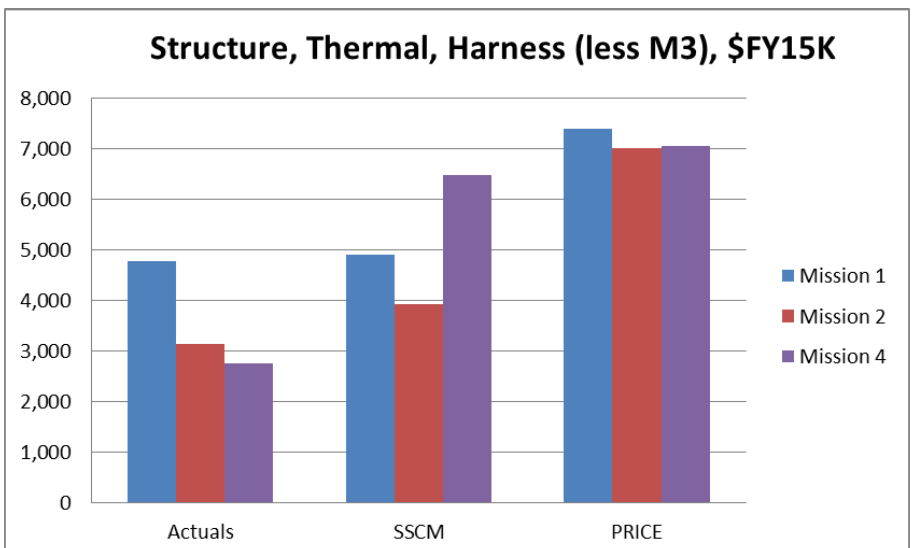


Overestimation of Power also makes intuitive sense:

- Class-D more likely to use existing architectures/BTP of proven flight designs
- Likely single-string with less rigorous testing given flight heritage
- ***Using traditional modeling techniques may unfairly penalize Class D Power***
- ***PRICE estimate over by 200%; SSCM 59%***

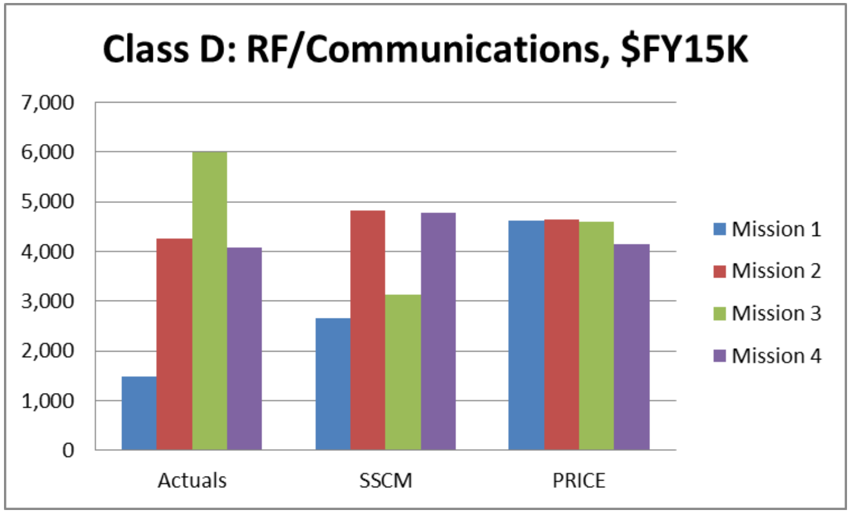
Spacecraft Hardware: Actuals vs. Predicted, Structure/Thermal/Harness

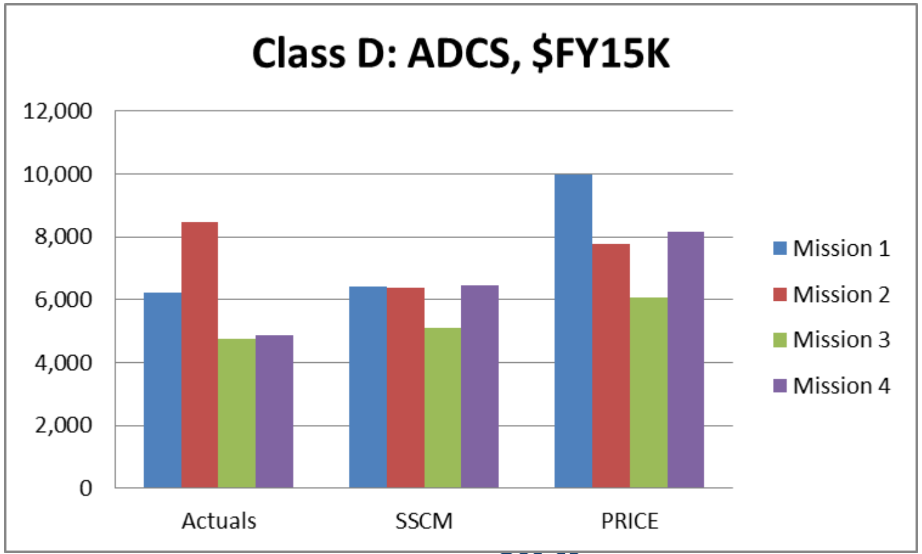




- Mission 3's structure actuals well outside expected value given mass and technical description (book-keeping error?)
- Removing M3 from the analysis for major structural elements, PRICE and SSCM both overestimated total cost (112% and 54%, respectively)
- ***Difference may be driven by design reuse and less rigorous testing requirements***

Spacecraft Hardware: Actuals vs. Predicted, ADCS & RF/Comm





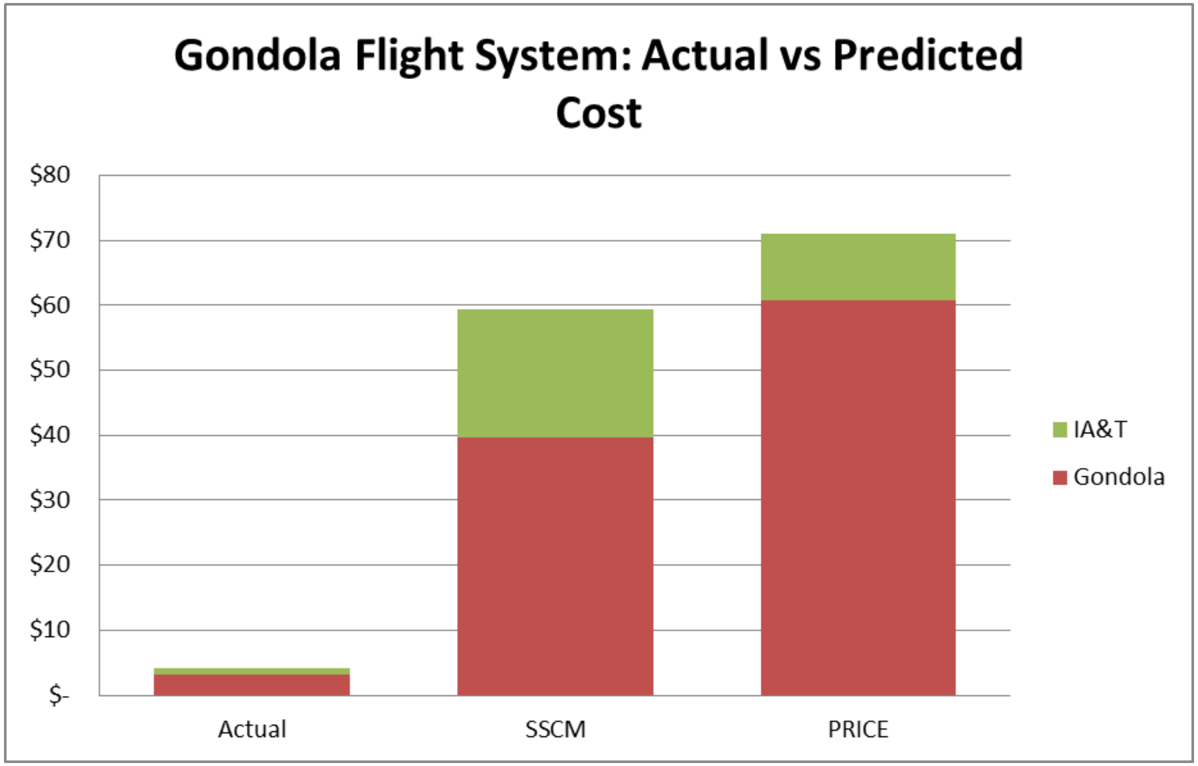
- ADCS, RF/Comm estimates more accurate, especially when using SSCM
- Both subsystems have high degree of purchased/TRL-9 components across all mission classes—estimates may be less subject to variation in NRE with Class D
- **PRICE estimates for RF are still 50% high on average**—caution should be used here with lower class missions

Balloon Gondolas: Actuals vs. Predicted

Balloon Gondola: Actual vs. Predicted Cost $FY15M							
Gondola Flight System Major WBS Elements	Representative New APL	Estimates		Delta, $		Delta, %	
		SSCM	PRICE-H	SSCM	PRICE-H	SSCM	PRICE-H
Gondola	**$ 3.17**	**$ 39.73**	**$ 60.70**	**$ 36.55**	**$ 57.53**	1152%	1813%
Structures/Mechanisms	*$ 1.16*	*$ 14.19*	$ 10.03	$ 13.03	$ 8.87	1121%	763%
Power	*$ 0.27*	*$ 6.53*	$ 7.25	$ 6.26	$ 6.99	2347%	2620%
C&DH	*$ 0.60*	*$ 6.31*	$ 11.35	$ 5.70	$ 10.75	944%	1778%
ADCS	*$ 0.28*	*$ 6.29*	$ 13.52	$ 6.02	$ 13.24	2173%	4780%
RF/Comm	*$ -*	*$ 3.25*	$ 1.78	$ 3.25	$ 1.78		
Thermal	*$ 0.10*	*$ 3.16*	$ 14.85	$ 3.06	$ 14.75	3142%	15131%
Harness	*$ 0.16*		$ 2.00	$ (0.16)	$ 1.84	-100%	1187%
Software	*$ 0.61*						
Gondola IA&T	**$ 0.97**	**$ 19.56**	**$ 10.32**	**$ 18.58**	**$ 9.35**	1910%	961%
Total Flight System	**$ 4.15**	**$ 59.28**	**$ 71.02**	**$ 55.14**	**$ 66.87**	**1330%**	**1613%**

- Gondolas are unique mission category—almost Class D-, without sufficient data to quickly validate costs using traditional modeling techniques
  - Not a spacecraft, but still conducting “space-like” science with precise payloads
  - Large dry mass (~2500kg) at low cost—largely structural frame
  - Many very low-cost, commercially procured items
- Testing qualifications and standards clearly lower than spacecraft; however, mission requirements not explicitly different according to 7120.5E
- **SSCM and PRICE-H both overestimate by over an order of magnitude when employed with minimal adjustments for balloon missions**

Balloon Gondola: Actuals vs. Predicted



Clearly, adjustments should be employed when estimating and validating balloon gondola costs—models representative of space-qualified hardware and not balloon missions

Spacecraft Hardware: Class D Adjustments for Future Estimates

- If accepted modeling tools—specifically PRICE—overestimate Class D hardware using nominal complexity values, what adjustments can be made to more accurately estimate spacecraft for Class D missions?
- Given the difference in estimated vs. realized costs in PRICE using nominal spacecraft complexity factors, we should see a noticeable difference in the calibration factors for Class D hardware at the subsystem level
  - ***The complexity input to PRICE is non-linear: small differences can quickly translate to very large differences in cost estimates***
- We calibrated each spacecraft/gondola at the subsystem level using realized cost and technical data from CADRe
  - Assumed subsystem-level average ratio of electronics/structural mass
    - E.g. 75% electronics, 25% structure for Avionics, 20% electronics, 80% structure for RF/Comm
  - Assumed 65%/35% NRE/RE on average (some variation at the subsystem level, particularly avionics and power which demonstrate higher NRE historically)
- ***This process quantifies efficiencies that exist independent of mass, which remains that key driver in most modeling tools***

Spacecraft Hardware: Class D Calibrations

Electronics Calibration: NAFCOM vs. Class D Average				
Subsystem	**NAFCOM**	**Class D**	**Delta**	**Sigmas**
RF/Comm	10.818	10.118	0.700	0.46
Attitude Control	10.638	9.660	0.977	0.74
Power	10.638	8.809	1.828	**1.76**
Avionics	10.772	8.864	1.908	**1.91**

- As expected, the electronics calibration factors for Power and Avionics are ***nearly 2 standard deviations*** away from the average NAFCOM factor
- Electronics calibrations are, on average, **1.22σ** away from the NAFCOM average

- Structural calibration factors for Power and Avionics are ***over two standard deviations*** away from the average NAFCOM factor, along with ADCS.
- Structural calibrations are, on average, **1.98 σ** away from the NAFCOM average

Structural Calibration: NAFCOM vs. Class D Average				
Subsystem	**NAFCOM**	**Class D**	**Delta**	**Sigmas**
RF/Comm	8.639	7.839	0.800	0.56
Attitude Control	10.192	7.950	2.242	**6.84**
Power	9.153	6.899	2.254	**2.05**
Structures/Mechanisms	8.473	8.201	0.272	0.24
Avionics	8.264	6.547	1.717	**2.66**
Thermal	8.868	8.487	0.381	0.33
Harness	8.332	7.371	0.961	**1.21**

Gondola Hardware: Class D Calibrations

Electronics Calibration: NAFCOM vs.Gondola Average				
Subsystem	**NAFCOM**	**Gondola**	**Delta**	**Sigmas**
Attitude Control	10.638	7.627	3.010	**2.28**
Power	10.638	7.961	2.676	**2.58**
Avionics	10.772	8.539	2.233	**2.24**

- The electronics calibration factors for gondolas **are all greater than 2σ away** from the NAFCOM averages
- This deviation occurs even after using a lower platform for the gondola calibration process

- Likewise, The structural calibration factors for gondolas are **all greater than 2σ away** from the NAFCOM averages

Structural Calibration: NAFCOM vs. Gondola Average				
Subsystem	**NAFCOM**	**Gondola**	**Delta**	**Sigmas**
Attitude Control	10.192	6.831	3.361	**10.25**
Power	9.153	6.485	2.668	**2.43**
Structures/Mechanisms	8.473	5.667	2.806	**2.45**
Avionics	8.264	6.359	1.906	**2.96**
Harness	8.332	7.371	0.961	0.80

Class-D Hardware Summary

- Based on actual vs. modeled costs, there are quantifiable hardware cost efficiencies for Class D spacecraft
  - Cost efficiencies exist independent of mass—low cost driven by reduced engineering complexity (BTP, strong heritage, less rigorous testing, etc.)
  - Lower cost also not driven by schedule—average B-D development of analyzed missions is 55 months
- At the total spacecraft level, SSCM does a reasonable job of predicting Class D Spacecraft cost
  - Estimates within 12% of total cost on average
  - However, SSCM still overpredicts Class D avionics and power subsystem costs
- PRICE-H overestimates total spacecraft hardware cost across all subsystems when using nominal complexity factors
  - Overpredicts even when assuming high TRL/minimal new design
  - Power and Avionics estimates over by >100%
- All models grossly overestimate gondola costs for balloon missions
  - High mass/very low complexity
  - Commercially procured parts with low reliability requirements
  - Short mission lifetime/more benign operating environment
  - BUE is a reasonable estimating methodology

PRICE-H estimates can be adjusted using calculated Class-D complexity factors--particularly helpful estimating power and avionics

Class-D Wrap Costs: PM/SE/MA

- Multiple analyses have demonstrated that hardware cost continues to be a strong predictor of mission-level PMSEMA costs
- There are quantifiable cost efficiencies with Class-D spacecraft hardware
- We analyzed both mission level PMSEMA and TOTAL PMSEMA (mission+spacecraft) to determine if:
  - Wrap costs scale with hardware and therefore reflect some tailoring of requirements?
  - PMSEMA wrap factors increase with Class-D missions due to a baseline FTEs that exceed the average cost-to-cost factor?
  - Increased requirements drive the cost-to-cost factor higher with Class-D (large PMSEMA support relative to the low cost of hardware)?

Wrap Costs: PM/SE/MA

Totals of 01, 02, 03 on 05, 06, 10			
	Average	StDev	coeff var
PM	7%	5%	0.67
SE	4%	1%	0.32
SMA	4%	1%	0.28
Total	15%	4%	0.28

All layers mgmt plus burden on hardware/software/all layers I&T			
	Average	StDev	coeff var
PM	22%	8%	0.39
SE	7%	0%	0.07
SMA	7%	2%	0.30
Total	35%	10%	0.29

All layers mgmt on hardware/software/all layers I&T/burden			
	Average	StDev	coeff var
PM	19%	9%	0.45
SE	7%	0%	0.06
SMA	6%	2%	0.29
Total	32%	10%	0.31

- Mission level PM/SE/MA averages 15% of total flight system costs (WBS 05,06,10)
- CADRe analysis shows range of 8% to 20%; average 14%
- Mission+Spacecraft PM/SE/MA averages 35% of total flight system cost (CADRe analysis shows range of 8% to 38%; average 33%
- Wrap factors, regardless of calculation method, are consistent with historical Class A/B missions
- ***Wrap costs are scaling with hardware costs***
    - Some efficiencies given lower hardware cost
    - Not marked difference, but consistent percentage of lower hardware cost translates to lower overall PM/SE/MA costs

Conclusions & Recommendations

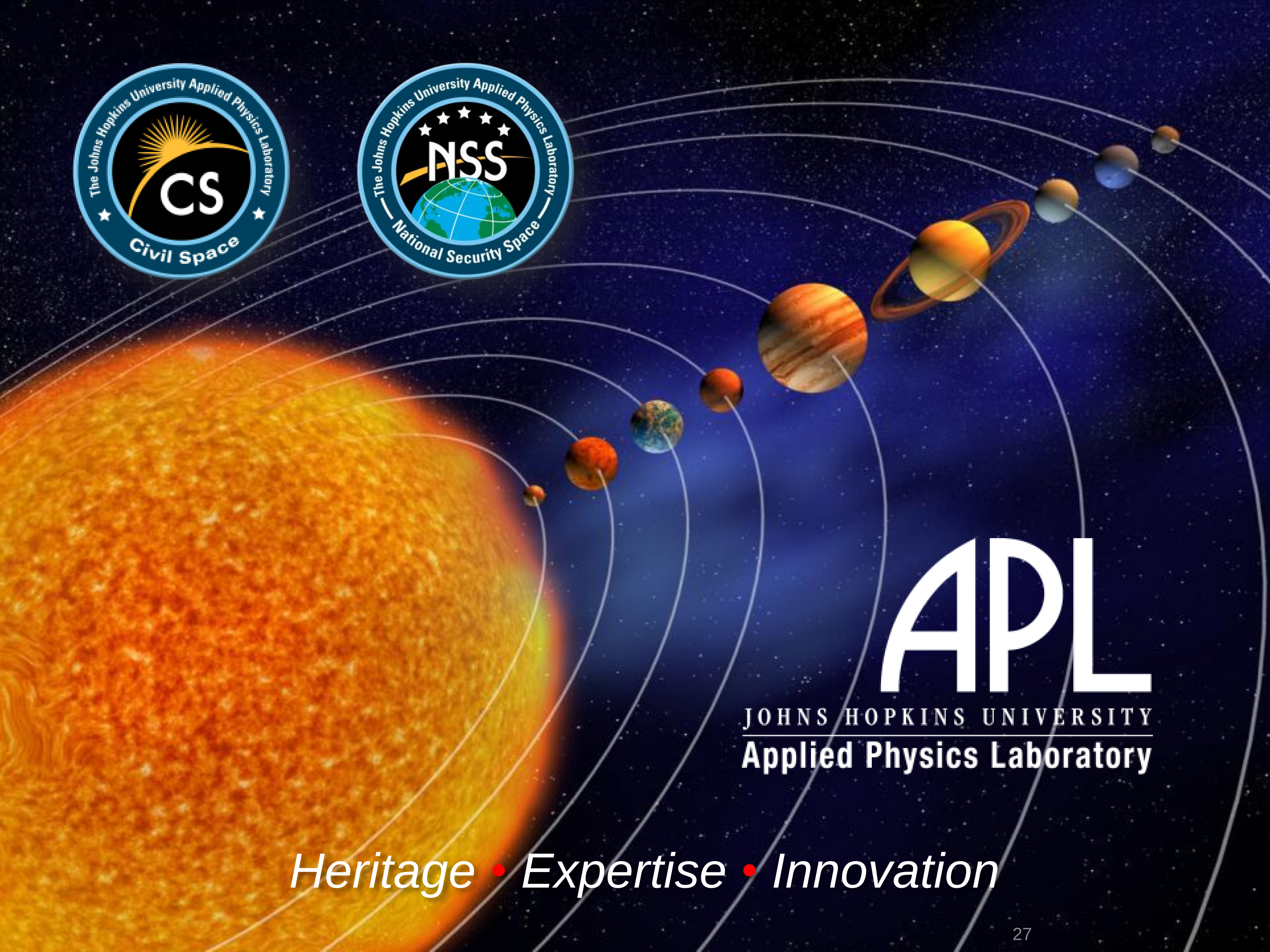
- We have reason to estimate Class-D hardware separately from Class A/B
  - Demonstrated efficiencies
  - Class D PRICE calibrations can be used as a starting point for more targeted estimates
  - …while we remain cognizant of the limitations of a small data set
- PM/SE/MA cost appears to scale with hardware, and averages 15% of total flight system costs at the mission level
  - Is requirements-tailoring for each mission contributing to reduced wrap costs?
  - More relaxed testing requirements at the hardware level, reduced hardware complexity overall may drive oversight costs down
- Hardware and associated wrap costs commensurate with mission risk classification
  - We should be wary of assigning Class A/B estimating processes and risk assessments to Class D missions
  - "One size fits all" estimating methodology not appropriate—feasible Class D missions could be unfairly assigned high cost risk/cost-prohibitive
  - Baseline estimates and risk assessments should take mission class into account

Opportunities for Future Research

- Obvious limitation of this analysis: limited data set
- Should cost risk analyses also reflect a more aggressive mission risk posture?
  - Given the existing database, risk adjusted estimates may doubly penalize Class D—both in the baseline estimate and in the assessment of overall cost risk
  - Is the 70^{th} percentile expectation too conservative for Class D?
- Analysis of Integration and Test costs
  - If there are demonstrated hardware efficiencies, this should theoretically reduce overall spacecraft testing costs
- Analysis of payload costs
  - Do instruments benefit from similar savings as spacecraft hardware?

Special Thanks

- Sally Whitley and Nicole Krepps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