Spacecraft and Support Function Cost Models for NASA PCEC

8/25/15

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OUTLINE

1. Introduction
2. Data Normalization
3. Project Management, Systems Engineering, Mission Assurance, and Integration & Test Model
4. S/C Subsystem Cost Model
5. Lessons Learned

PCEC Cost Modeling Approach & Current Progress

- **Approach**
  - Collect & Normalize a data set from projects with launch CADRe's
  - Explore estimating methodologies covering NASA WBS elements using the normalized data set
- **Current Progress**
  - Data has been collected/normalized for 42 recently launched robotic science spacecraft projects (unmanned)
  - A PCA-based estimating methodology has been developed for Project Management (PM), Systems Engineering (SE), Mission Assurance (MA), and Integration & Test (I&T)
  - A hybrid approach has been developed for Spacecraft Subsystems
- **Improvements to these methodologies have been identified and are in progress**
  - Enhanced methodologies, Additional missions, Validation with data from recently launched missions

NASA Robotic Science Mission PCEC Costing Tool Enhancements

Engineering Cost Office

NAFCOM uses a mix of approaches to capture mission development costs

SOCM is typically used to estimate MO&DA

NAFCOM	NASA WBS		PCEC
Historical-based Wrap Factors	1	Program Management	PM/SE/MA/I&T Model
	2	Systems Engineering	
	3	Mission Assurance	
Pass-thru	4	Science	*Pass-thru*
Instrument CERs + Wraps	5	Payload	NICM + PM/SE/MA/I&T Model
Historical-based Wrap Factors	5.1	P/L Project Management	PM/SE/MA/I&T Model
	5.2	P/L Systems Engineering	
	5.3	P/L Mission Assurance	
Instrument CERs	5.4	Instruments	Instrument CERs and/or NICM
	5.4.1-n	Instrument #1-n	
Historical-based Wrap Factors	5.5	P/L IAT + GSE	*tbd*
	5.6	P/L GSE	*tbd*
S/C CERs + Wraps	6	Spacecraft	S/C S/S + PM/SE/MA/I&T Model
Historical-based Wrap Factors	6.1	S/C Project Management	PM/SE/MA/I&T Model
	6.2	S/C Systems Engineering	
	6.3	S/C Mission Assurance	
Multi-variable Subsystem & Some Component CERs	6.5	Flight Elements	S/C Subsystem Model
	6.5.1-n	Flight Element #1-n	
	6.5.1.1	Structure & Mech.	
	6.5.1.2	Thermal	
	6.5.1.3	Power	
	6.5.1.4	C&DH	
	6.5.1.5	Communications	
	6.5.1.6	ACS	
	6.5.1.7	Propulsion	
Historical-based Wrap Factors	6.6	S/C IAT + GSE	PM/SE/MA/I&T Model
	6.9	S/C GSE	
Historical-based Wrap Factors	7	MOS	*tbd*
Lookup Table	*8*	*Launch Services*	*Pass-thru*
Historical-based Wrap Factors	9	GDS	*tbd*
	10	System Level IAT	PM/SE/MA/I&T Model
Pass-thru	*11*	*E/PO*	*Pass-thru*

- Currently, PCEC includes Excel-based updates of NAFCOM12 relationships
- Future versions will include new models for all WBS elements, with multiple available approaches for some items
- An updated approach for estimating Project Support functions (PM/SE/MA/I&T) has been developed
- Preliminary PCEC S/C CERs recently completed

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PCEC CADRe Data Normalization
Primary Objective

- **Provide a set of normalized cost data to support NASA cost modeling efforts and future versions of the PCEC**
  - **Cover robotic science spacecraft projects (unmanned)**
  - Contracting Fees/Burdens/Taxes, Contributions, Full Cost Accounting, External Impacts, and other characteristics affect cost data from past missions in different ways
  - For cost modeling, a data set reflecting a common set of assumptions is needed
- **Other significant requirements**
  - Provide mapping to the most current NASA standard WBS
  - Provide visibility into the assumptions affecting the normalized data
  - Build on the experience from NAFCOM and resources in REDSTAR

NASA STANDARD WBS

WBS #	*Item*
1.0	Program Management
2.0	Systems Engineering
3.0	Mission Assurance
4.0	Science
5.0	Payload
6.0	Spacecraft
7.0	MOS
8.0	Launch Services
9.0	GDS
10.0	System Level IAT
11.0	E/PO

PCEC CADRe Data Normalization Approach & Products

APPROACH

- **Developed an approach for a revised data normalization process**
  - Past approaches lacked clear visibility into how data points were normalized
  - Plans for a Normalization Study were reviewed/approved by the MSFC ECO lead
  - Selected 20 projects to include to assess the credibility and impact of a revised data normalization approach and developed a quick turn-around schedule (~6wks)
  - Selected projects were split into 2 Groups; Interim results covering the first group (12 projects) were provided on 10/21/13 and process adjustments implemented
  - The revised process was then applied to 42 projects

PRODUCTS

- **Cost Assessment Reports (CARs)**
  - CARs document assumptions associated with each step of the normalization process and provide normalized results that can be used for cost modeling
  - Each CAR has a corresponding Excel workbook with additional details
- **Figure-of-Merit (FOM) Analyses**
  - Four FOM analyses are included with each CAR: Data Quality, S/C Heritage, Prototypes/Spares, Parts Quality/Redundancy
  - The Data Quality FOM captures the degree to which the raw cost data provided visibility into each step of the normalization process
  - The other FOM analyses attempt to capture technical characteristics that affect cost

PCEC CADRe Data Normalization Challenges

- **Many items complicate using the cost data for modeling and making fair comparisons between projects; Examples include:**
  - Fee/Burden/Tax arrangements for major contracts vary by project
  - Full Cost Accounting changes add uncertainty/error
  - Schedules are continually changing at all WBS levels
  - Impact from Long Lead procurements can skew NRC/RC splits
  - PM/SE/MA/I&T is impacted by Contributed (uncosted) items
  - Changing NASA culture over past 10-20 years
  - Projects have varying approaches to parts quality, prototyping, etc.
  - Flight heritage significantly affects most cost elements
  - Costs are often affected by "External Impacts"
  - And More

PCEC CADRe Data Normalization
Current Project Data Set

- The 42 missions with normalized cost data are shown here
- The set covers recent missions and includes representatives from each NASA science discipline
- The normalization process shows the traceability to the official CADRe data
  - All assumptions and changes have been documented
- The normalized data for each of these has been provided to the lead organizations for their review

MISSION	Launch Date	Lead Org PM	Lead Org Flt Sys	NASA Program
1 TDRSS K-L	1/23/14	GSFC	Boeing	Space Comm
2 MAVEN	11/18/13	GSFC	LMA	Planetary
3 LADEE	9/6/13	GSFC	ARC	Planetary
4 IRIS	6/27/13	GSFC	LMMS	Astrophysics/SMEX
5 Van Allen Probes	8/30/12	GSFC	APL	Heliophysics/LWS
6 NuSTAR	6/13/12	JPL	OSC	Astrophysics/Explorer
7 MSL	11/26/11	JPL	JPL/LMA	Planetary/Mars Expl
8 GRAIL	9/10/11	JPL	LMA	Planetary/Discovery
9 Juno	8/5/11	JPL	LMA	Planetary/New Frontiers
10 Glory	3/4/11	GSFC	OSC/Swales	Earth Sciences
11 GOES (-P)	3/4/10	GSFC/NOAA	Boeing/SGT	Earth Sciences
12 SDO	2/11/10	GSFC	GSFC	Heliophysics
13 WISE	12/14/09	JPL	BATC	Astrophysics/Explorer
14 LCROSS	6/18/09	ARC	NG	Planetary/Discovery
15 LRO	6/18/09	GSFC	GSFC	Planetary
16 KEPLER	3/6/09	JPL	BATC	Astrophysics/Discovery
17 OCO	2/24/09	JPL	OSC	Earth Science
18 IBEX	10/19/08	SwRI	OSC	Astrophysics/Explorer
19 Dawn	9/27/07	JPL	OSC/JPL	Planetary/Discovery
20 Phoenix	8/4/07	JPL	LMA	Planetary
21 AIM	4/25/07	LASP	OSC	Heliophysics
22 THEMIS	2/17/07	UCB	Swales	Astrophysics/Explorer
23 STEREO	10/26/06	GSFC	APL	Heliophysics
24 CLOUDSAT	4/28/06	GSFC	BATC	Earth Sciences
25 NEW HORIZONS	1/19/06	APL	APL	Planetary/New Frontiers
26 MRO	8/12/05	JPL	LMA	Planetary/Mars Expl
27 DEEP IMPACT	1/12/05	JPL	BATC	Planetary/Discovery
28 Swift	11/20/04	GSFC	Spectrum Astro	Astrophysics/Explorer
29 MESSENGER	8/3/04	APL	APL	Planetary/Discovery
30 Spitzer	8/25/03	JPL	LMA	Astrophysics
31 MER	6/10/03	JPL	JPL	Planetary/Mars Expl
32 GALEX	4/28/03	JPL	OSC	Astrophysics/Explorer
33 RHESSI	2/5/02	UCB	Spectrum Astro	Heliophysics
34 TIMED	12/7/01	APL	APL	Earth Sciences
35 GENESIS	8/8/01	JPL	LMA	Planetary/Discovery
36 Mars Odyssey	7/7/01	JPL	LMA	Planetary/Mars Expl
37 WMAP	6/30/01	GSFC	GSFC	Astrophysics/Explorer
38 WIRE	3/5/99	GSFC	GSFC	Astrophysics/Explorer
39 TRACE	4/2/98	GSFC	GSFC	Astrophysics/Explorer
40 Cassini	10/15/97	JPL	JPL	Planetary/Outer Planets
41 Mars Global Surveyor	11/7/96	JPL	LMA	Planetary/Mars Expl
42 NEAR	2/17/96	APL	APL	Planetary/Discovery

Earth Sci	Heliophy
Astrophy	Planetary

PCEC CADRe Data Normalization

Normalization Process Steps Summary

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START
Raw (Unadjusted) Project Data →

STEP 1
Inflate to Common Fixed Year $ →

STEP 2
Allocate to NASA WBS →

STEP 3
Account for Mgmt, Fees, & Burdens →

OUTPUT A
NASA WBS by Yr w/o Fees or Burdens

STEP 4
Full Cost Accounting Adjustments →

STEP 5
Account for Contributions →

OUTPUT B
NASA WBS by Yr w/ FCA & Contributions but w/o Fees or Burdens

STEP 6
Development Profile Phasing - *Schedule & Long Lead Items* →

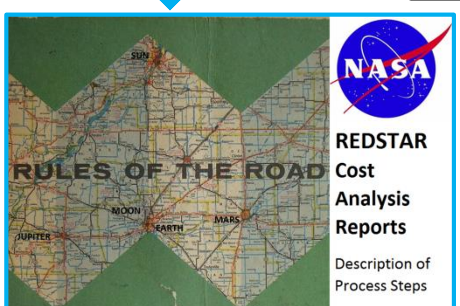
STEP 7
Removal of Costs for Multiple Units →

OUTPUT C
NASA WBS by Phase (*normalized to a single protoflight unit*)

STEP 8
Removal of Costs from External Impacts →

OUTPUT D
NASA WBS by Phase w/o External Impacts

Additional detail covering each process step is documented in the "Rules of the Road"



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PCEC PM-SE-MA-I&T Model Objective & Approach

Objective: ***Develop an improved estimating methodology to capture Management, Systems Engineering, Mission Assurance, and Integration & Test costs***

- Explore alternatives to the "wrap factor" approach
- **Cover robotic science spacecraft projects (unmanned)**

Effort began with proof-of-concept rapid prototype development using an approach similar to what is used for the NASA Space Operations Cost Model (SOCM)

2nd Modeling effort explored three alternatives:

- Standard regression approach
- Constructive, SOCM-like approach (relies on expert judgment)
- Statistical approach using Principal Component Analysis (PCA)

PCEC PM-SE-MA-I&T Model
Rapid Prototype Inputs

- **Individual input weightings are assigned for each WBS element (PM/SE/MA/I&T) in each phase (Design/Fab/I&T/Launch Ops)**

Inputs Used for Rapid Prototype

Group			1	2	3	4	5
Program-matics	1a	NASA PROGRAM	EV, Other	Explorer	Discovery	New Frontiers	Flagship
	1b	MISSION RISK CLASS	Class D	Class C	Class B		Class A
	1c	MISSION TARGET/TYPE	Earth Orbiting or Lunar	Mercury, Venus, Mars	Small Bodies	Outer Planets	Planetary Lander or Sample Return
Lead Type	2a	LEAD ORGANIZATION TYPE	Univ	Govt	APL/JPL/SwRI	Industry	Mix/Int'l
	2b	FLIGHT SYSTEM ORGANIZATION TYPE	Univ	Govt	APL/JPL/SwRI	Industry	Mix/Int'l
	2c	PAYLOAD ORGANIZATION TYPE	Univ	Govt	APL/JPL/SwRI	Industry	Mix/Int'l
Lead Exp	3a	LEAD ORG EXPERIENCE	Extensive		Nominal		Minimal
	3b	FLIGHT SYSTEM LEAD ORG EXPERIENCE	Extensive		Nominal		Minimal
	3c	PAYLOAD LEAD ORG EXPERIENCE	Extensive		Nominal		Minimal
	4	INHOUSE SCOPE	All Flight Elements Inhouse	Most Flight Elements Inhouse	System contractor for Flight HW	Multiple (2+) major system contractors	Multiple major developers including Gov+Ind
	5	INTERNATIONAL PARTICIPATION	No Int'l HW or Col's	No Int'l HW; Some Int'l CoIs	Minimal Int'l HW; Some Int'l CoIs	$2-10M of Int'l HW + Int'l Col's	Sign Int'l HW + Int'l Col's
FltSys Size/Cplx	6a	FLIGHT SYSTEM MASS	<200kg	200-400kg	400-600kg	600-1000kg	>1000kg
	6b	FLIGHT SYSTEM POWER	<250W	250-500W	500-700W	700-1000W	>1000W
	6c	FLIGHT SYSTEM HERITAGE&TRL	No TRL<7	1-2 TRL<7 items	3-4 TRL<7 items	Several TRL<7 items	Significant ATD for key elements
Pyld Size/Cplx	7a	PAYLOAD MASS	<50kg	50-100kg	100-150kg	150-300kg	>300kg
	7b	PAYLOAD POWER	<50W	50-100W	100-300W	300-500W	>500W
	7c	PAYLOAD HERITAGE&TRL	No TRL<7	1-2 TRL<7 items	3-4 TRL<7 items	Several TRL<7 items	Significant ATD for key elements

Add'l Input Candidates

Management: # of Major External I/Fs, S/C Contractor Cost, S/C In-House Cost, Degree of Off-site Oversight, Scope of Identified Risks

Sys Engrng: # of Reqts, Simulation/Test Scope, Contingencies/Margins, Redundancy, Prototyping, Funded Schedule Margin, Unfunded Schedule Slack

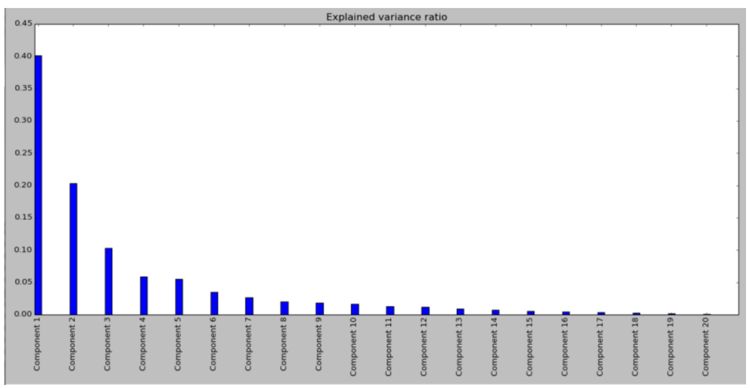
Mission Assurance: Parts Quality, Redundancy, Sparing

I&T: # of Flight Elements, Prototyping, Facility Reqts, GSE, Spares, I&T Schedule Margin/Slack

PCEC PM-SE-MA-I&T Model
Principle Component Analysis Approach

1) A correlation matrix was generated to get a sense of the of the dependency between variables.
   - Several of the variables appeared to be correlated, making PCA an attractive method to apply to the data set.

LN $k-FY14 Per Month	1																				
LN DIRECTED or AO	0.25	1																			
LN MISSION RISK CLASS	-0.6	-0.5	1																		
LN MISSION DESTINATION	0.55	-0	-0.2	1																	
LN FLIGHT SYSTEM TYPE	0.16	0.07	0.09	0.37	1																
LN LEAD ORGANIZATION	0.66	0.29	-0.4	0.22	0.13	1															
LN FLIGHT SYSTEM ORGANIZATION	0.34	-0	0.06	0.09	0.12	0.27	1														
LN PAYLOAD ORG.	0.39	0.14	-0.2	-0	0.05	0.52	0.39	1													
LN FLIGHT SYSTEM LEAD ORG. EXPERIENCE	0.21	0.14	-0.1	0	-0.2	0.3	0.31	0.12	1												
LN PAYLOAD LEAD ORG. EXPERIENCE	0.63	0.2	-0.5	0.34	-0.1	0.26	0.33	0.15	0.49	1											
LN FLIGHT SYSTEM MASS	0.74	0.38	-0.5	0.48	0.11	0.55	0.07	0.3	0.07	0.48	1										
LN FLIGHT SYSTEM POWER	0.6	0.21	-0.4	0.06	-0.1	0.57	0.08	0.3	0.06	0.32	0.72	1									
LN FLIGHT SYSTEM HERITAGE & TRL	0.02	-0.1	0.01	-0	-0.2	0.02	0.3	0.02	0.44	0.38	-0.1	-0.2	1								
LN PARTS RATING	0.76	0.19	-0.6	0.54	0.22	0.52	-0	0.34	0.03	0.55	0.71	0.58	-0.2	1							
LN # OF KEY SPACECRAFT CONTRACTORS	0.43	0.04	-0.1	0.46	0.27	0.16	0.18	0.3	-0.2	0.06	0.38	0.19	-0.1	0.33	1						
LN PAYLOAD MASS	0.27	0.3	-0.3	-0.1	-0.1	0.44	0.11	0	0.43	0.2	0.28	0.31	0.14	0.19	-0.4	1					
LN PAYLOAD POWER	0.39	0.42	-0.4	-0.1	-0.1	0.46	0.2	0.28	0.36	0.41	0.54	0.55	0.12	0.34	-0	0.7	1				
LN # OF PAYLOAD ELEMENTS	0.08	0.06	-0.1	0.31	0.12	-0.4	-0.3	-0.2	-0.2	0.15	0.18	-0.2	-0.2	0.12	0.23	-0.4	-0.2	1			
LN # OF KEY PAYLOAD CONTRACTORS	-0.1	-0.1	-0.1	0.12	-0.1	-0.2	-0.3	-0.2	-0.2	-0.2	-0	-0.1	-0.3	-0.1	-0.1	-0.1	-0.3	0.58	1		
LN IN-HOUSE SCOPE	0.34	0.18	-0.3	0.33	0.16	0.1	-0.3	0.03	0.03	0.3	0.49	0.16	-0.1	0.47	0.34	-0.1	0.08	0.47	0.08	1	
LN INTERNATIONAL PARTICIPATION (HW)	-0	0.15	-0.1	-0.2	-0.1	0.13	-0	0.12	0.23	-0.1	-0.1	0.09	-0.2	-0.1	0.03	-0	0.03	-0.2	-0.3	-0.1	1



2) The principal components were determined using an algorithm developed in Python.
   - The first 6 principal components which account for 85% of variance in the data set were selected and used to determine which of the 20 variables were most likely related to cost.

3) For each of the 21 data sets examined, 4 subsets of the 20 variables were run through a multiple regression routine to determine the new cost estimating relationships.

PCEC PM-SE-MA-I&T Model Modeling Performance Comparisons

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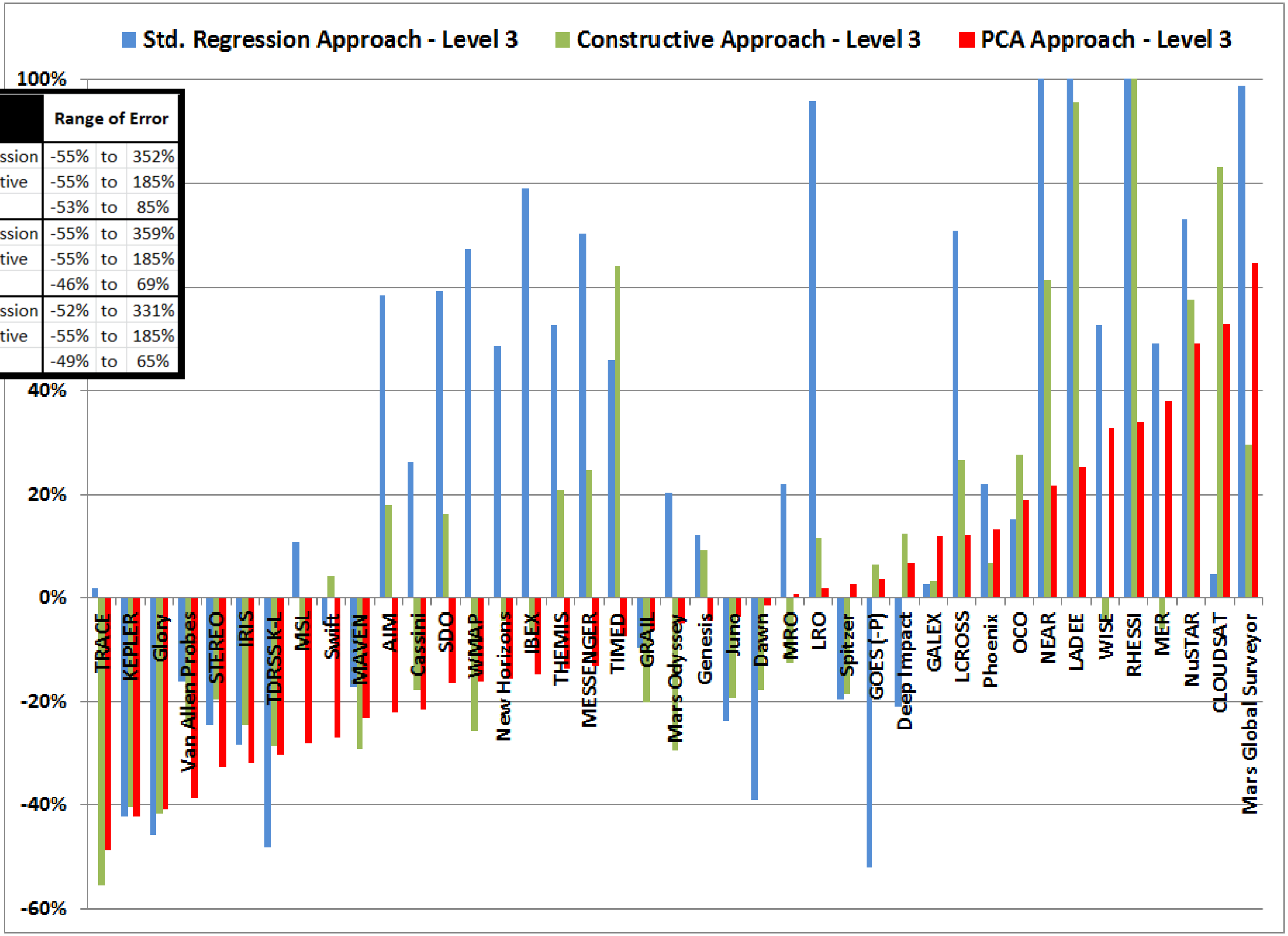
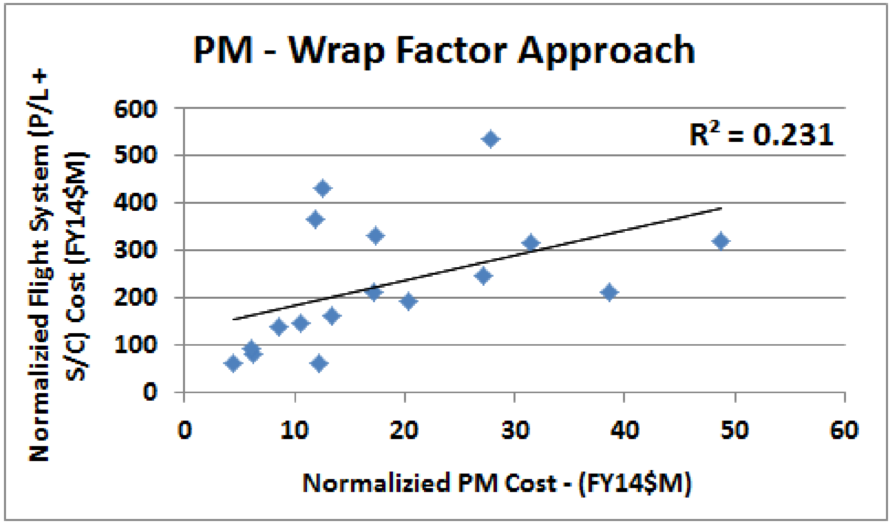
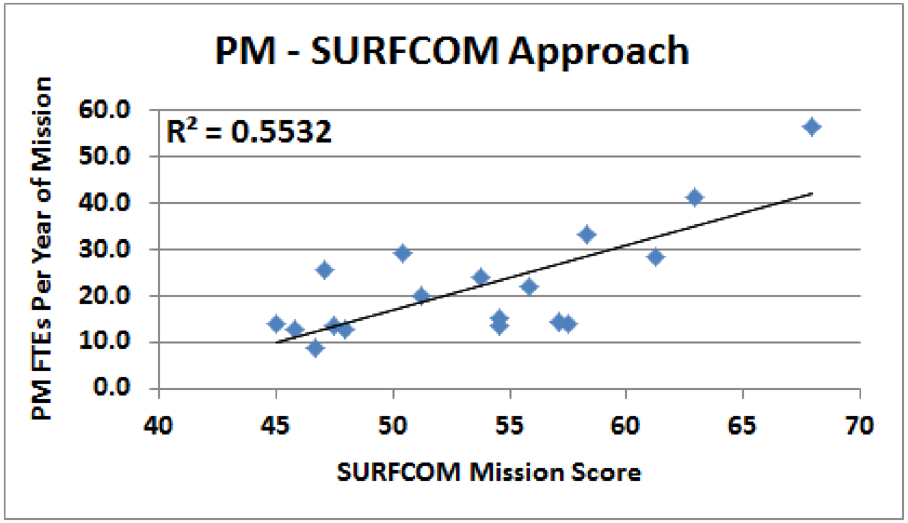
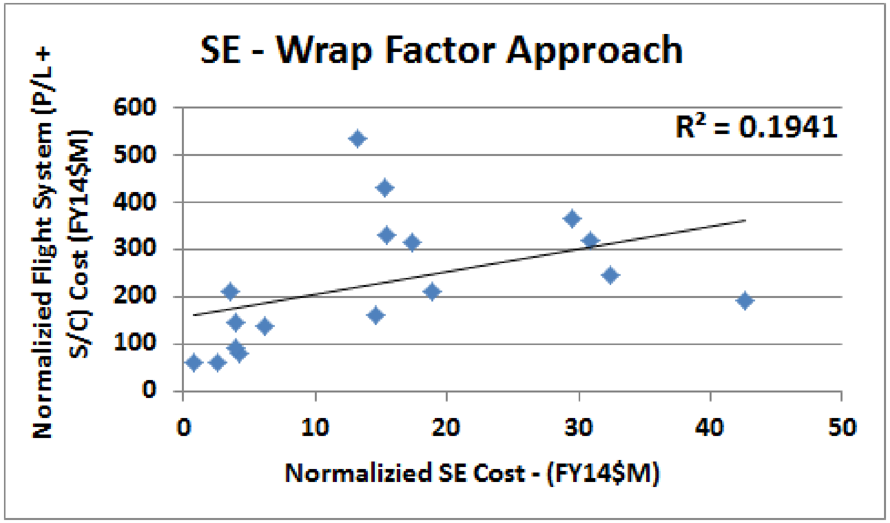


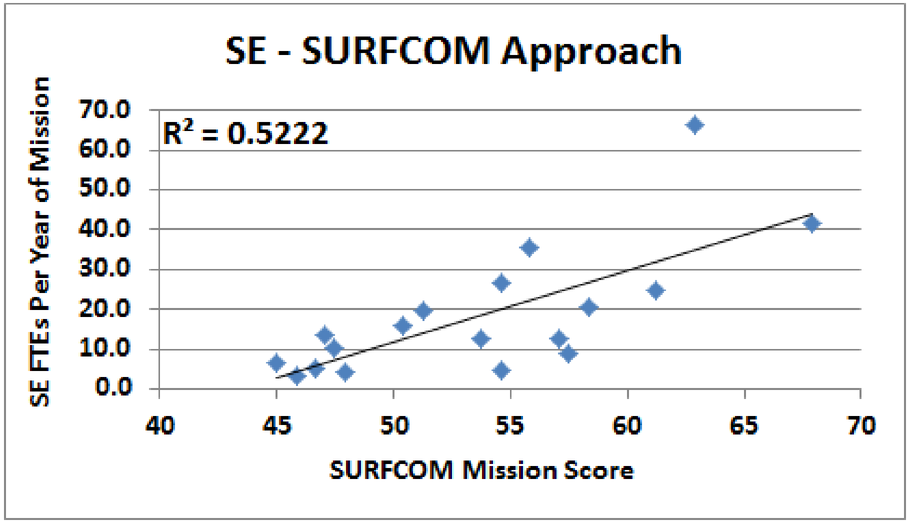
		Range of Error		
Level 1	Std. Regression	-55%	to	352%
	Constructive	-55%	to	185%
	PCA	-53%	to	85%
Level 2	Std. Regression	-55%	to	359%
	Constructive	-55%	to	185%
	PCA	-46%	to	69%
Level 3	Std. Regression	-52%	to	331%
	Constructive	-55%	to	185%
	PCA	-49%	to	65%

PCEC PM-SE-MA-I&T Model Comparison to Wrap Factors, 1 of 2



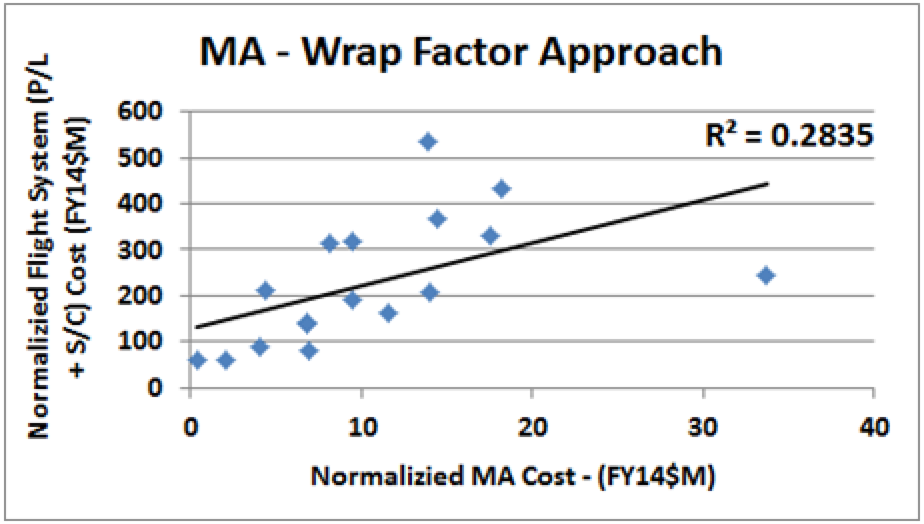


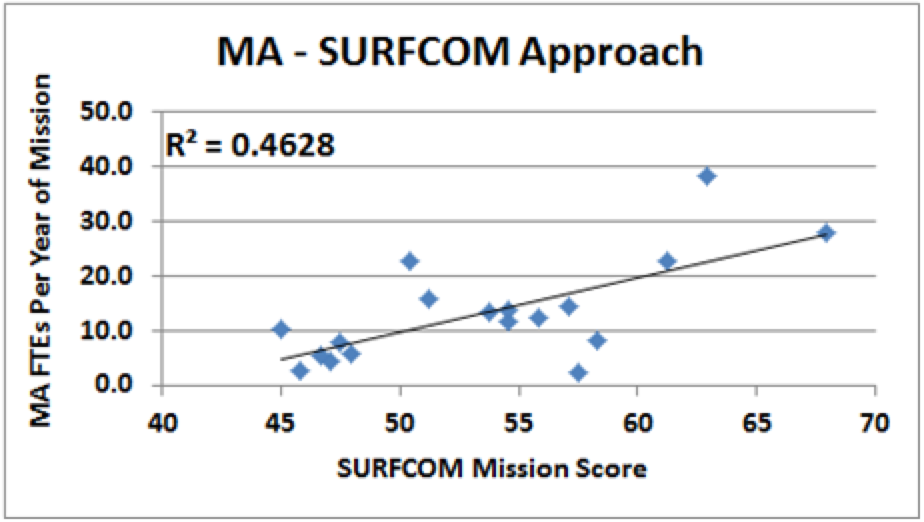


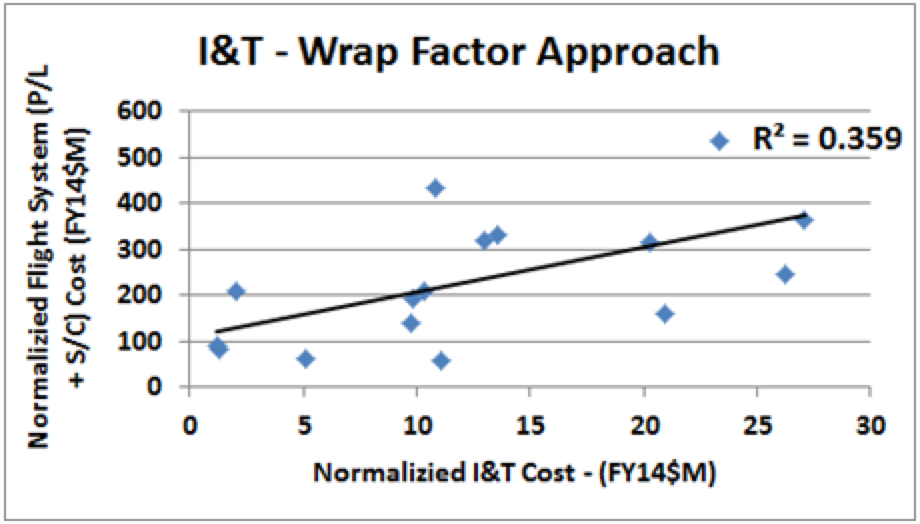


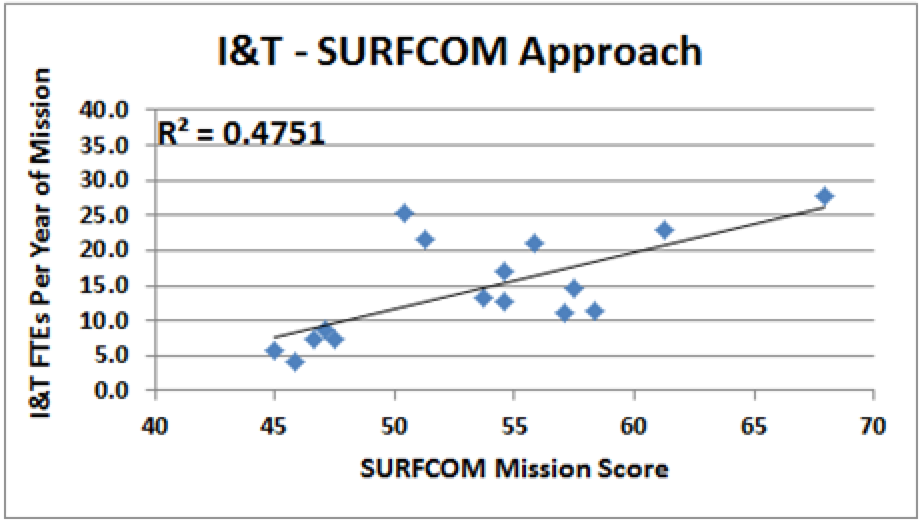
SURFCOM = Support Function Cost Model

PCEC PM-SE-MA-I&T Model Comparison to Wrap Factors, 2 of 2









SURFCOM = Support Function Cost Model

Project Support Allocations Between Project-Payload-S/C and Development Phases

Engineering Cost Office

- The PCEC Project Support Model combines Project Management, Systems Engineering, Mission Assurance and Integration & Test from WBS 1/2/3/5/6/10
- Development phases include Design, Fabrication, Integration & Test, and Launch Operations & Check-Out (L+30)
- The model's PCA based algorithms used in this version include "Level 1" and "Level 2"
  - Level 1: Single CER for combined PM/SE/MA/I&T across all WBS elements and phases
  - Level 2: 4 separate CERS for each of the 4 functions
  - Level 3: 16 CERs covering each of the 4 functions across each of the 4 development phases (not included due to significant variability by phase – totals similar to Level 2)

NASA WBS items included for this modeling effort

NASA WBS (augmented)

WBS #	Item
1.0	Program Management
2.0	Systems Engineering
3.0	Mission Assurance
4.0	Science
5.0	Payload
5.1	P/L PM
5.2	P/L SE
5.3	P/L MA
5.4	Instrument #1
5.xx	Instrument *n*
5.70	P/L Software
5.80	P/L IAT
5.90	P/L GSE
6.0	Spacecraft
6.1	S/C PM
6.2	S/C SE
6.3	S/C MA
6.4	Structure & Mech. (SC 1)
6.5	Thermal (SC 1)
6.6	Power (SC 1)
6.7	C&DH (SC 1)
6.8	Communications (SC 1)
6.9	ACS (SC 1)
6.10	Propulsion (SC 1)
6.11	Harness (SC 1)
6.12-6.43	Repeat 6.4-6.11 for each Flt Element
6.70	S/C Software
6.80	S/C IAT
6.90	S/C GSE
7.0	MOS
8.0	Launch Services
9.0	GDS
10.0	System Level IAT
11.0	E/PO

- The basis for allocations between WBS 1/2/3/10 and WBS 5/6 and to the development phases are provided here, but these are treated as inputs in the current model version due to data variability at the lower levels

PM/SE/MA Distributions between Project, Payload, and S/C

Engineering Cost Office

- Data shown here is combined PM/SE/MA from WBS 1/2/3/5/6 from the normalized data
  - Splits are shown between Project-level (WBS 1/2/3/10), Payload-level (WBS 5) and S/C (WBS 6)
- Since there is significant variability between Projects or Programs, database averages representing all missions shown are used

	Total	Payload	Spacecraft
All Missions	**57%**	**12%**	**31%**
Heliophysics	**61%**	**4%**	**36%**
	63%	1%	36%
	58%	7%	35%
Astrophysics	**62%**	**15%**	**23%**
	42%	39%	19%
	63%	0%	37%
	45%	26%	29%
	49%	5%	46%
	45%	29%	26%
	54%	46%	0%
	79%	0%	21%
	89%	1%	10%
	71%	5%	24%
	57%	8%	35%
	90%	8%	3%
Planetary	**54%**	**9%**	**37%**
	66%	12%	22%
	86%	7%	7%
	80%	1%	19%
	35%	4%	60%
	24%	10%	67%
	61%	3%	35%
	46%	8%	46%
	56%	6%	38%
	75%	25%	0%
	84%	14%	2%
	46%	8%	45%
	39%	15%	46%
	45%	7%	48%
	38%	11%	50%
	23%	8%	69%
Earth Science	**48%**	**20%**	**32%**
	48%	6%	46%
	50%	39%	11%
	45%	16%	38%

PM/SE/MA Distributions to Development Project Phases

Engineering Cost Office

- Data shown here are PM/SE/MA distributions across the phases
- Since there is significant variability between Projects or Programs, database averages representing all missions shown are used

All	37%	27%	28%	8%	41%	35%	21%	3%	38%	33%	24%	6%
Helio	24%	36%	28%	11%	56%	21%	21%	2%	23%	48%	22%	7%
Astro	35%	33%	24%	8%	23%	48%	26%	3%	35%	39%	21%	5%
Planetary	41%	17%	32%	10%	49%	26%	21%	4%	42%	24%	28%	6%
Earth	32%	43%	21%	4%	51%	43%	6%	0%	36%	41%	19%	3%
	Proj				Pyld				S/C			
Mission	Des	Fab	I&T	LOCO	Des	Fab	I&T	LOCO	Des	Fab	I&T	LOCO
New Horizons	20%	18%	52%	11%	60%	7%	23%	9%	50%	22%	24%	4%
MESSENGER	60%	25%	12%	3%	33%	44%	20%	3%	57%	43%	0%	0%
Deep Impact	31%	23%	35%	11%	37%	53%	10%	0%	42%	16%	38%	4%
STEREO	20%	52%	15%	13%	81%	20%	0%	-2%	21%	76%	2%	2%
Dawn	33%	19%	46%	2%	24%	16%	50%	9%	31%	19%	41%	10%
LCROSS	24%	17%	27%	32%	73%	17%	8%	2%	49%	25%	22%	4%
SDO	28%	21%	42%	10%	30%	21%	43%	7%	26%	20%	42%	11%
GOES N-P	47%	31%	16%	6%	99%	1%	0%	0%	39%	36%	18%	7%
Glory	26%	44%	24%	5%	23%	67%	9%	1%	23%	46%	30%	1%
GALEX	16%	61%	16%	7%	15%	72%	8%	5%	14%	64%	14%	9%
IBEX	44%	17%	25%	13%					52%	9%	27%	12%
GRAIL	43%	20%	27%	10%	37%	35%	21%	7%	35%	27%	28%	10%
NuSTAR	36%	14%	33%	16%	17%	18%	63%	3%	39%	18%	32%	11%
MRO	62%	23%	14%	0%	70%	20%	11%	0%	51%	20%	22%	8%
CloudSat	23%	54%	22%	0%	32%	61%	8%	0%	47%	43%	10%	0%
WISE	48%	26%	17%	9%	41%	32%	19%	8%	42%	37%	13%	8%
Kepler	53%	20%	21%	7%	25%	33%	41%	1%	54%	28%	15%	3%
MSL	29%	13%	41%	17%	42%	53%	3%	2%	31%	36%	25%	8%
LADEE	53%	1%	37%	9%								
Van Allen Probes	47%	12%	30%	11%	53%	21%	24%	1%	50%	18%	24%	8%
Juno	49%	25%	23%	3%	45%	24%	27%	4%	31%	31%	34%	5%
Phoenix	49%	9%	31%	11%	54%	11%	28%	7%	43%	12%	34%	11%
THEMIS	46%	16%	32%	5%					57%	22%	20%	1%
Swift	21%	3%	73%	2%	0%	82%	18%	0%	47%	27%	26%	0%
TIMED	39%	41%	17%	3%	36%	57%	5%	2%	27%	70%	2%	1%
GENESIS	39%	12%	38%	10%	57%	13%	28%	2%	37%	15%	40%	8%
WMAP	16%	58%	19%	8%	7%	16%	75%	3%	0%	43%	55%	1%

I&T Distributions between Project-Payload-S/C and Development Phases

Engineering Cost Office

- Data shown here are I&T distributions between Project-Payload-S/C (WBS 10/5/6) and across the development phases
- Since there is significant variability between Projects or Programs, database averages representing all missions shown are used

All	23%	28%	37%	13%	35%	11%	54%
Helio	14%	36%	34%	16%			
Astro	20%	33%	33%	14%	39%	16%	45%
Planetary	25%	22%	40%	13%	34%	1%	66%
Earth	22%	45%	28%	6%	26%	31%	43%
	I&T				I&T		
Mission	Des	Fab	I&T	LOCO	Proj	Pyld	S/C
New Horizons	0.07	0.03	0.59	0.31			
MESSENGER	0.07	0.25	0.49	0.18	12%	3%	85%
Deep Impact	0.42	0.22	0.33	0.03	36%	0%	63%
STEREO	0.05	0.47	0.21	0.27			
Dawn	0.28	0.21	0.45	0.07	55%	0%	45%
LCROSS	0.28	0.33	0.29	0.10			
SDO	0.22	0.26	0.47	0.05			
GOES N-P	0.37	0.37	0.18	0.07			
Glory	0.06	0.52	0.37	0.05	52%	23%	25%
GALEX	0.02	0.80	0.15	0.03			
IBEX	0.26	0.09	0.38	0.26	21%	8%	71%
GRAIL	0.32	0.27	0.26	0.15			
NuSTAR	0.32	0.15	0.32	0.20	13%	7%	80%
MRO	0.41	0.24	0.26	0.08	5%	1%	95%
CloudSat					0%	40%	60%
WISE	0.42	0.38	0.13	0.08			
Kepler	0.53	0.28	0.16	0.03	46%	43%	11%
MSL	0.12	0.22	0.48	0.18			
LADEE	0.19	0.00	0.58	0.23			
Van Allen Probes	0.34	0.12	0.39	0.14	18%	0%	82%
Juno	0.19	0.26	0.47	0.08	83%	0%	17%
Phoenix	0.41	0.10	0.32	0.17	28%	0%	72%
THEMIS	0.29	0.25	0.38	0.08	42%	27%	31%
Swift	0.01	0.00	0.64	0.35			
TIMED	0.15	0.52	0.32	0.01			
GENESIS	0.37	0.15	0.40	0.07			
WMAP	0.00	0.22	0.62	0.16			
Cassini	0.03	0.38	0.49	0.11			
MGS	0.39	0.44	0.13	0.03			
NEAR	0.50	0.41	0.08	0.02			
MAVEN	0.05	0.24	0.51	0.19			

PCEC PM-SE-MA-I&T Model
Project Support Allocation Notes

- The database averages are approximate starting points and distributions used should represent the implementation approach
  - Reasonable levels for these functions should be included in WBS 5/6 based on the scope of the Payload and S/C
  - The remaining portion is defaulted to the Project-level (WBS 1/2/3/10)
- Phase distributions are also approximate starting points and should be assigned consistent with the implementation approach being modelled

OUTLINE

Engineering Cost Office

1. Introduction
2. Data Normalization
3. Project Management, Systems Engineering, Mission Assurance, and Integration & Test Model
4. S/C Subsystem Cost Model
5. Lessons Learned

PCEC S/C MODEL

Engineering Cost Office

STARTING INPUT CANDIDATES

Includes > 100 inputs from NASA cost and other models

MISSION CANDIDATES

Includes 42 launch NASA robotic Earth/space science projects; Cost data has been "normalized" to facilitate use for modelling

1st screen based on data availability from the normalized data set (42 missions) = ~100 input candidates/mission

Principle Component Analysis

- Uses PCA to reduce the input set to the key drivers of cost differences
- Regression analyses are performed with the key inputs
- Approximately 10-20 inputs per S/C subsystem

Regression using Expert Judgment

- Uses PCA results and expert judgment to select key regression inputs
- Approximately 10-20 inputs per subsystem

Hybrid Approaches

- Uses regression to develop initial estimates
- Adjustment factors have been developed to refine the estimate with additional inputs

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PCEC S/C MODEL – Initial Inputs

- **Multiple information sources have been reviewed to generate the initial input candidate list, including mass & performance metrics from:**
  - CADRe: Fields in Part B (technical)
  - Cost Models: Aerospace Corp SSCM & COBRA, PRICE Space Missions (update of SAIC/Chicago Cost Model), and NAFCOM

INPUT CANDIDATES

PROJECT/MISSION
- Mission Risk Class
- Mission Target/Type
- Lead Organization
- Flight System Lead Organization
- Payload Lead Organization
- Flight System Lead Experience
- Payload Lead Experience
- # of Key S/C Contractors
- # of Key Payload Contractors
- Degree of In-House Scope
- International HW Participation
- Directed or AO
- Subsystem Lead Organization
- Subsystem Lead Experience
- # of Key Subcontractors
- Degree of In-House Scope

SCHEDULE
- Design Time (ATP-CDR)
- Fabrication Time (CDR-SIR)
- I&T Time (SIR-Ship)
- LO Time (Ship-Launch)
- CO Time (Launch-On-orbit CO)

FLIGHT SYSTEM
- Flight System Type
- Flight System Mass
- Flight System Power
- Flight System Heritage
- Flight System Advanced Technology
- Flight System New Design
- Flight System Design Modifications
- Parts Rating
- Payload Mass
- Payload Power
- # of Payload Elements
- # of flight system elements
- Operating Environment
- Radiation Environment

STRUCTURES & MECHANISMS
- Mass
- Load Carrying Shell/Truss Material
- # of Articulated Structures
- # of Deployed Structures

THERMAL
- Mass
- Thermal Operating Environment
- Thermal Control Type
- Radiator Material
- Insulation Type
- Power, Heaters (W)

PROPULSION/RCS
- Mass
- Engine 1 Thrust
- Engine 2 Thrust
- Engine 3 Thrust
- Ion PPU Power
- Ion Engine Thrust
- Tank Material
- Type of Propulsion System
- Propellant Mass
- Number of Thrusters

COMMAND & DATA HANDLING
- Mass
- Board Form Factor
- # of Boards
- Data Storage Capacity
- Onboard FSW, SLOC
- FSW Reuse
- Processor Type

COMMUNICATIONS
- Mass
- Uplink Band
- Downlink Band
- # of Bands
- Transmitter Power
- Max. Instrument Data Output
- Peak Uplink Data Rate
- Peak Downlink Data Rate
- Average Downlink Data Rate
- Average Uplink Data Rate
- HGA Assembly Material
- HGA Diameter (m)
- Max. Distance from Sun (AU)

GUIDANCE, NAV, & CONTROL
- Mass
- Pointing Accuracy
- Pointing/Knowledge Requirements
- Pointing Stability, Jitter
- Reaction Wheel Torque
- Slew Rate
- Control Type (3 Axis, Spinner, other)

POWER
- Mass
- Battery Capacity
- Battery Type/Chemistry
- Average Payload Power
- Peak Payload Power
- OSRs Needed?
- BOL Power @ 1 AU
- Array Area (m^2)
- Active Cell Area (m^2)
- End of Life Power

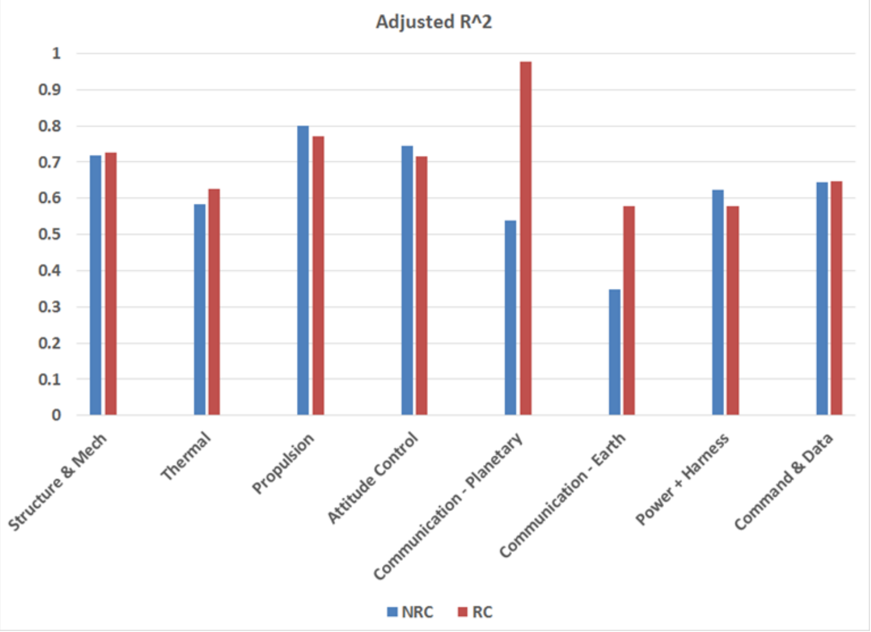
HARNESS
- Mass
- Additional EMI/Radiation Shielding
- End of Life Power

PCEC S/C MODEL Statistics Example

- These statistics represent regression results for Non-Recurring (NRC) and Recurring Costs (RC) after screening the inputs using PCA
- Generally, accuracy is reasonable for most subsystems
- Splitting near-Earth S/C (EO) from Planetary (PL) was explored for all subsystems but appears to mainly affect Communications
  - Communications is an example of a subsystem that likely needs a revised candidate input set
- After an acceptable set of regression inputs is established, candidate inputs for adjustments can be identified
  - Will leverage inputs not used in the regression with adjustments supported by analysis of residuals

Statistics	*Structure & Mech*		*Thermal*		*Propulsion*		*Attitude Control*	
	NRC	*RC*	*NRC*	*RC*	*NRC*	*RC*	*NRC*	*RC*
R-squared:	0.75	0.76	0.64	0.64	0.84	0.80	0.78	0.75
Adj. R-squared:	0.72	0.73	0.58	0.63	0.80	0.77	0.75	0.72
F-statistic:	22.44	23.13	11.94	66.29	22.58	23.54	23.15	20.08
Prob (F-statistic):	2.77E-10	1.84E-10	1.02E-06	7.43E-10	5.50E-08	7.56E-08	6.41E-10	3.70E-09
No. Observations:	43	43	40	40	28	28	39	39
Df Residuals:	37	37	34	38	22	23	33	33
Df Model:	5	5	5	1	5	4	5	5

Statistics	*Communication*				*Power + Harness*		*Command & Data*	
	NRC - EO	*NRC-PL*	*RC - EO*	*RC - PL*	*NRC*	*RC*	*NRC*	*RC*
R-squared:	0.38	0.67	0.60	0.99	0.67	0.60	0.69	0.68
Adj. R-squared:	0.35	0.54	0.58	0.98	0.62	0.58	0.64	0.65
F-statistic:	11.16	5.08	27.03	59.46	16.36	26.31	14.36	23.10
Prob (F-statistic):	3.64E-03	4.96E-03	6.05E-05	2.98E-05	1.77E-07	1.06E-07	2.14E-07	3.05E-08
No. Observations:	20	22	20	21	38	38	38	37
Df Residuals:	18	15	18	6	33	35	32	33
Df Model:	1	6	1	14	4	2	5	3



PCEC S/C MODEL Constructive Adjustments

Engineering Cost Office

- Adjustment factors have been developed to apply to the Regression-based S/C Subsystem CER results
  - Different factor sets were tested to minimize errors & maximize the # of missions estimated within +/-40%
  - 8 additional inputs are used -> System & Subsystem Heritage & Parts, Mission Class, Mission Type, Design & Fab times
  - All 8 additional inputs are the same as used for the PCEC PM-SE-MA-I&T model

<- Higher Cost   Lower Cost ->

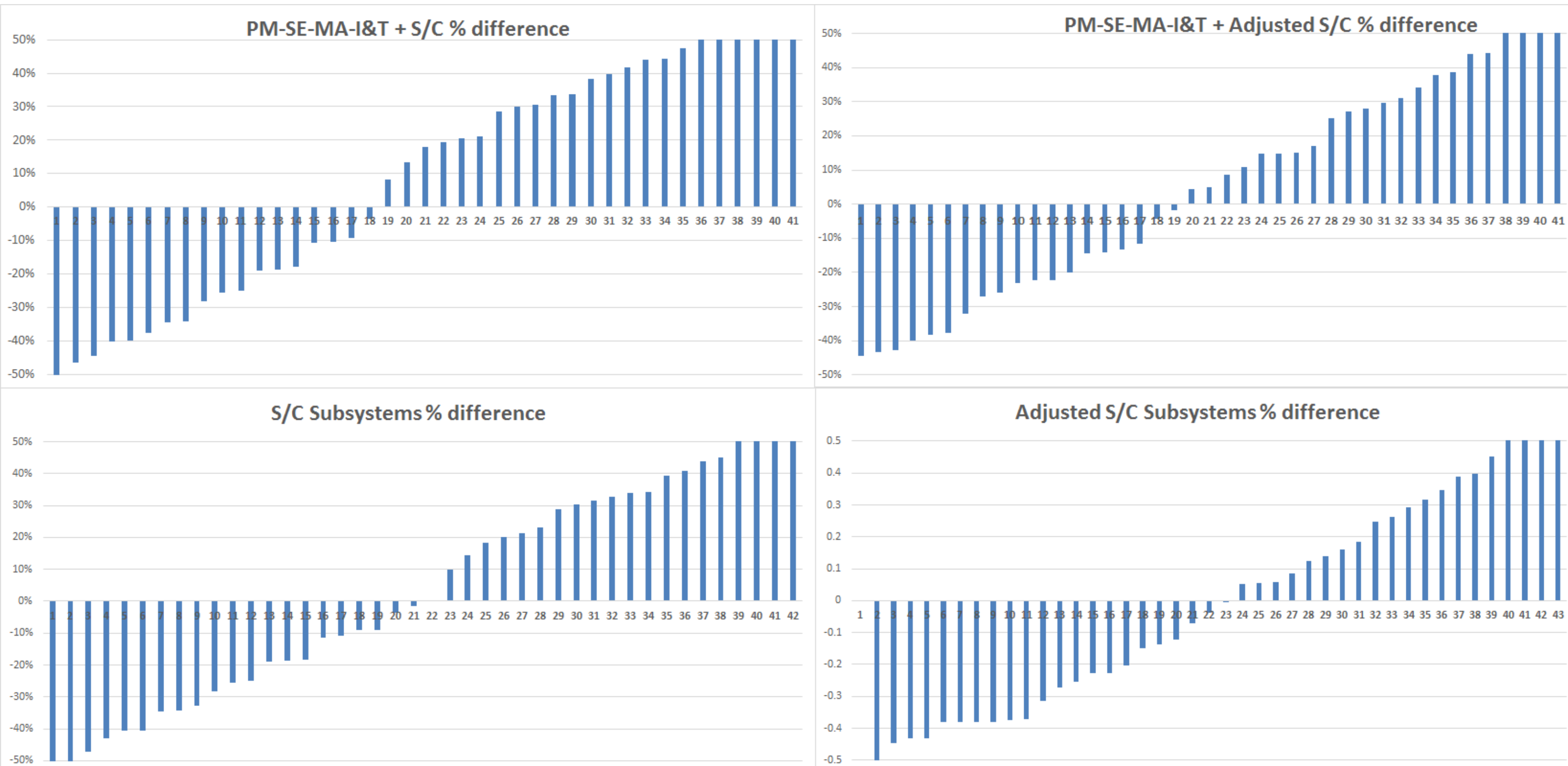
	System-Level Heritage	Sys-Lvl Parts	Subsys-Level Heritage	Subsys-Level Parts	Mission Class	Mission Type	Design Time, yrs	Fab+I&T Time, yrs
1	Exact Copy	<Space Qual	Exact Copy	<Space Qual	Class D	Earth	<1	<1
2					Class C	Astrophy	1-2	1-2
3					Class B	Helio	2-3	2-3
4	Minor Mod	Low Qual/ No Redund	Minor Mod	Low Qual/ No Redund	Class A	Planetary	3-4	3-4
5						Outer Pl	4-5	4-5
6	Major Mod	Med Qual/ Limited Redund	Major Mod	Med Qual/ Limited Redund		Mars	5-6	5-6
7							6-7	6-7
8	New/ Standard	High Qual/ Sign Redund	New/ Standard	High Qual/ Sign Redund			7-8	7-8
9							9-10	9-10
10	All TRL<7	Highest Qual/ Full Redund	All TRL<7	Highest Qual/ Full Redund			>10	>10

RESULTS	NRC+RC	NRC+RC
Avg Error	adjusted	Unadj
Earth	4%	54%
Astrophy	-3%	7%
Helio	-2%	6%
Planetary	1%	3%
Mars	-5%	-15%
Outer Pl	-6%	-11%
Plan+OP	-1%	-1%
Total	*-2%*	*5%*
Pts missed	*10*	*17*

- **Costs and inputs for System-Level & Subsystem-Level Heritage & Parts have been taken from the Cost Analysis Reports (CADRe-derived) to derive comparisons**

PCEC S/C MODEL Constructive Adjustments

- Estimate differences compared to actuals are shown here for the S/C Subsystem model, with and without adjustments
- Combined performance with the PM-SE-MA-I&T Model is also compared here



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NASA SPACE MISSIONS MODELLING LESSONS LEARNED

- Principle Component Analysis (PCA) can help identify a manageable subset of potential costing inputs that are the main contributors to cost differences from a much larger candidate set
- A consistent approach for data normalization is essential; Programmatic differences between the projects can strongly influence official costs
  - PCEC normalization adjusts the data to a defined set of rules/procedures
- Do not trust regression results without a thorough sanity check
  - Often, "associative" instead of "causal" inputs can yield counter-intuitive results (that may be misdirected); Best approach maximizes utilization of available "causal" inputs
  - It is important to understand reasons for outliers, which can lead to model enhancements
- A combination of PCA, regression, and constructive modelling approaches appears to offer many benefits over reliance on a single technique
  - Enhances flexibility to capture unique aspects associated with NASA robotic science missions
  - Adjustments to regression results need to be supported by data analysis
- Accuracy of technical and cost data should always be reviewed and questioned – differences often exist in assumptions behind different values for the same item from different sources