PCEC Robotic Missions

Updates for v2.4

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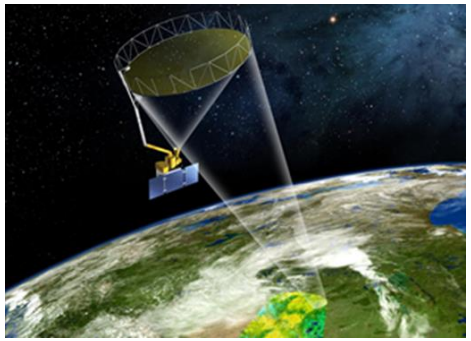
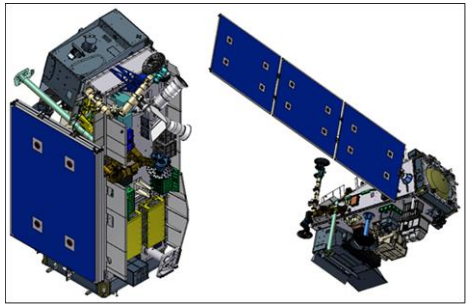
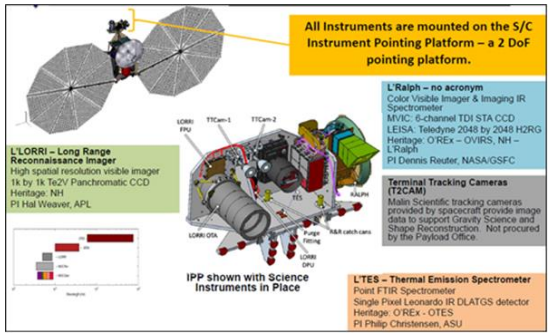
NASA Cost & Schedule Symposium

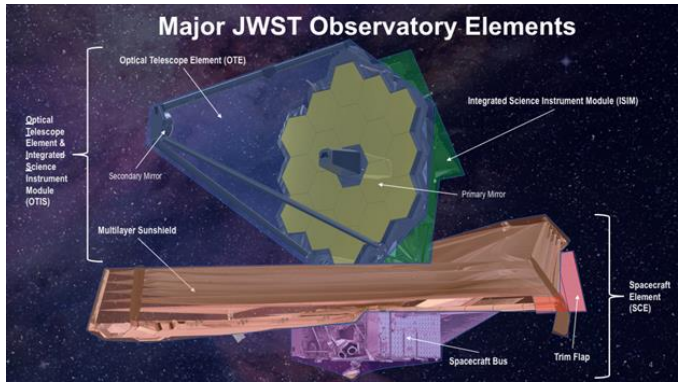
April 24, 2024

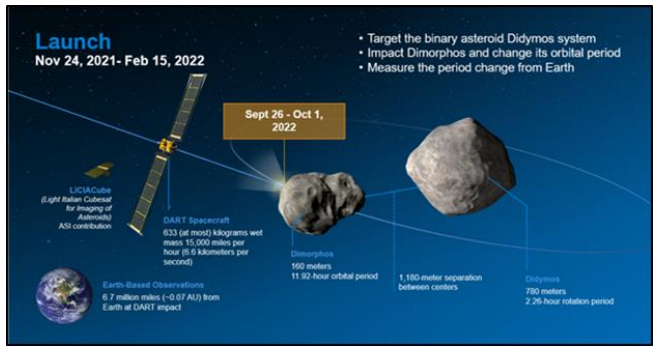


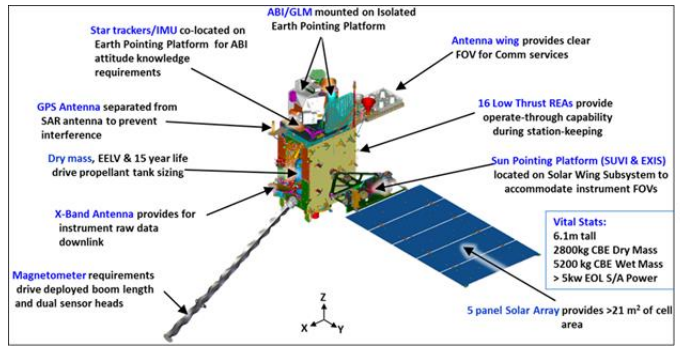


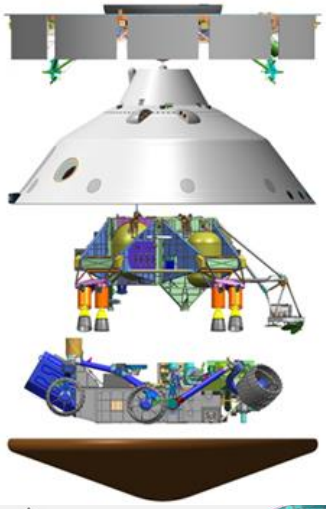


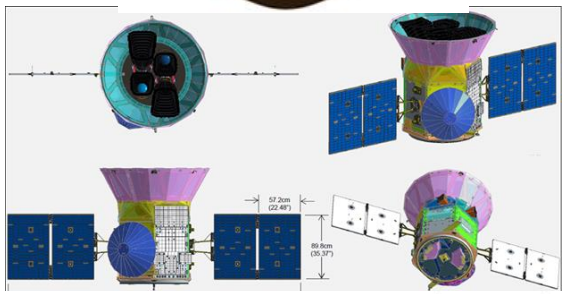
Graphics are New Missions in PCEC v2.4

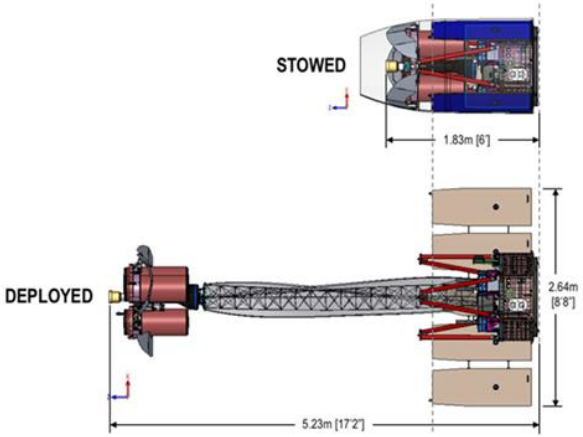












PCEC – Updates for v2.4 OUTLINE

1. PCEC Robotic Mission Database

- New missions since v2.3, Robotic Mission CER Development Database & Input Candidates, Data Normalization Updates

2. PCEC v2.4 Robotic Mission CER Updates

- Characterize the evolving PCEC database, characterize data outliers, and examine model performance

3. Future Plans

PCEC Robotic Mission Database

- Database covers 59 missions and 70 separate flight elements

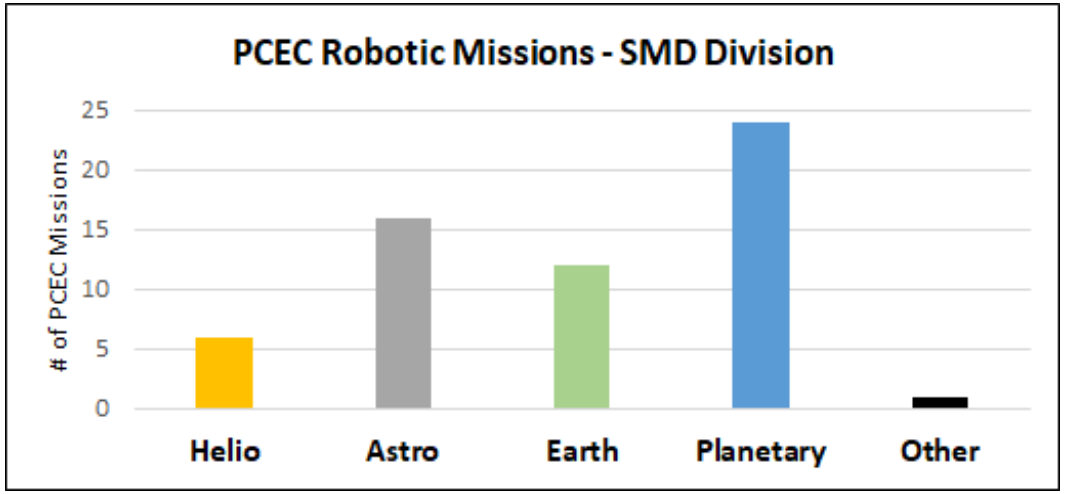
MISSION	Launch Date	Lead Org PM	Lead Org Flt Sys	NASA Program	Mission Risk Class
Missions for PCEC v2.3					
1 TDRSS K-L	1/23/14	GSFC	Boeing	Space Comm	Class A
2 MAVEN	11/18/13	GSFC	LMA	Planetary	Class C/D
3 LADEE	9/6/13	GSFC	ARC	Planetary	Class B
4 IRIS	6/27/13	GSFC	LMMS	Astrophysics/SMEX	Class C/D
5 Van Allen Probes	8/30/12	GSFC	APL	Heliophysics/LWS	Class B
6 NuSTAR	6/13/12	JPL	OSC	Astrophysics/Explorer	Class C/D
7 MSL	11/26/11	JPL	JPL/LMA	Planetary/Mars Expl	Class B
8 GRAIL	9/10/11	JPL	LMA	Planetary/Discovery	Class C/D
9 Juno	8/5/11	JPL	LMA	Planetary/New Frontiers	Class B
10 Glory	3/4/11	GSFC	OSC/Swales	Earth Sciences	Class C/D
11 GOES (-P)	3/4/10	GSFC/NOAA	Boeing/SGT	Earth Sciences	Class A
12 SDO	2/11/10	GSFC	GSFC	Heliophysics	Class B
13 WISE	12/14/09	JPL	BATC	Astrophysics/Explorer	Class C/D
14 LCROSS	6/18/09	ARC	NG	Planetary/Discovery	Class C/D
15 LRO	6/18/09	GSFC	GSFC	Planetary	Class B
16 KEPLER	3/6/09	JPL	BATC	Astrophysics/Discovery	Class C/D
17 OCO	2/24/09	JPL	OSC	Earth Science	Class C/D
18 IBEX	10/19/08	SwRI	OSC	Astrophysics/Explorer	Class C/D
19 Dawn	9/27/07	JPL	OSC/JPL	Planetary/Discovery	Class B
20 Phoenix	8/4/07	JPL	LMA	Planetary	Class B
21 AIM	4/25/07	LASP	OSC	Heliophysics	Class C/D
22 THEMIS	2/17/07	UCB	Swales	Astrophysics/Explorer	Class C/D
23 STEREO	10/26/06	GSFC	APL	Heliophysics	Class B
24 CLOUDSAT	4/28/06	GSFC	BATC	Earth Sciences	Class C/D
25 NEW HORIZONS	1/19/06	APL	APL	Planetary/New Frontiers	Class B
26 MRO	8/12/05	JPL	LMA	Planetary/Mars Expl	Class B
27 DEEP IMPACT	1/12/05	JPL	BATC	Planetary/Discovery	Class B
28 Swift	11/20/04	GSFC	Spectrum Astro	Astrophysics/Explorer	Class C/D
29 MESSENGER	8/3/04	APL	APL	Planetary/Discovery	Class B
30 Spitzer	8/25/03	JPL	LMA	Astrophysics	Class A
31 MER	6/10/03	JPL	JPL	Planetary/Mars Expl	Class B
32 GALEX	4/28/03	JPL	OSC	Astrophysics/Explorer	Class C/D
33 RHESSI	2/5/02	UCB	Spectrum Astro	Heliophysics	Class C/D
34 TIMED	12/7/01	APL	APL	Earth Sciences	Class C/D
35 GENESIS	8/8/01	JPL	LMA	Planetary/Discovery	Class C/D
36 Mars Odyssey	7/7/01	JPL	LMA	Planetary/Mars Expl	Class C/D
37 WMAP	6/30/01	GSFC	GSFC	Astrophysics/Explorer	Class C/D
38 WIRE	3/5/99	GSFC	GSFC	Astrophysics/Explorer	Class C/D
39 TRACE	4/2/98	GSFC	GSFC	Astrophysics/Explorer	Class C/D
40 Cassini	10/15/97	JPL	JPL	Planetary/Outer Planets	Class A
41 Mars Global Surveyor	11/7/96	JPL	LMA	Planetary/Mars Expl	Class B
42 NEAR	2/17/96	APL	APL	Planetary/Discovery	Class B
43 GPM	2/27/14	GSFC	BATC	Earth Sciences	Class B
44 OCO-2	7/2/14	JPL	OSC	Earth Sciences	Class C/D
45 MMS	3/12/15	GSFC	GSFC	Astrophysics/Explorer	Class C/D
46 OSIRIS-REx	9/8/16	GSFC	LMA	Planetary/New Frontiers	Class B
47 GOES-R	11/19/16	GSFC/NOAA	Boeing/SGT	Earth Sciences	Class B
48 CYGNSS	12/15/16	SwRI	SwRI	Earth Sciences	Class C/D
49 InSight	5/5/18	JPL	LMA	Planetary/Discovery	Class B

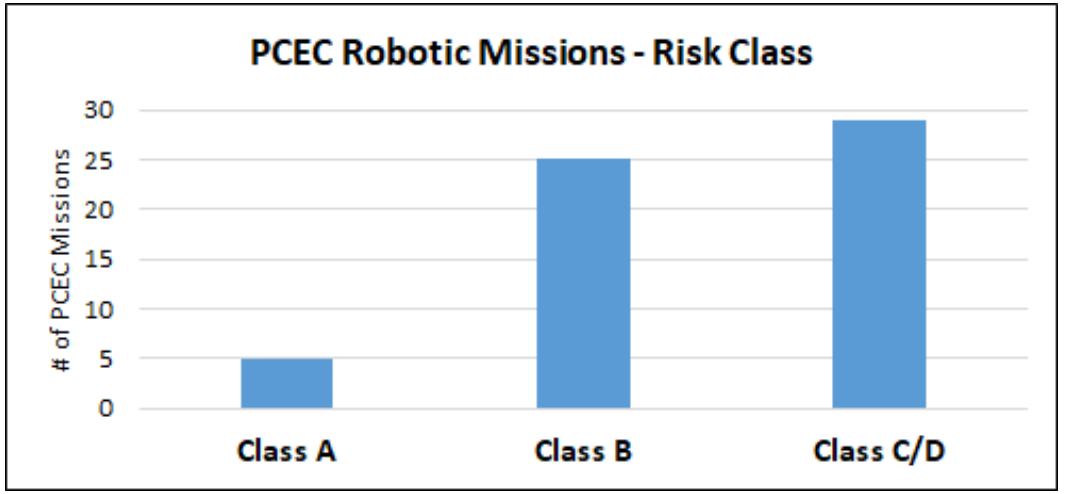
MISSION	Launch Date	Lead Org PM	Lead Org Flt Sys	NASA Program	Mission Risk Class
New Missions with Normalized Data					
50 SMAP	1/31/15	JPL	JPL	Earth Sciences	Class C/D
51 JPSS-1	11/10/17	GSFC	BATC	Earth Sciences	Class B
52 Solar Probe	8/6/18	GSFC	APL	Heliophysics	Class B
53 Mars 2020	7/30/20	JPL	JPL	Planetary	Class B
54 TESS	3/20/18	GSFC	OSC	Astrophysics/Explorer	Class C/D
55 IXPE	12/9/21	MSFC	Ball	Astrophysics/Explorer	Class C/D
56 DART	11/23/21	APL	APL	Planetary	Class C/D
57 JWST	12/25/21	GSFC	NG	Astrophysics	Class A
58 Lucy	10/16/21	GSFC	LMSS	Planetary	Class B
59 GOES-T	3/1/22	GSFC	LMSS	Earth Sciences	Class B

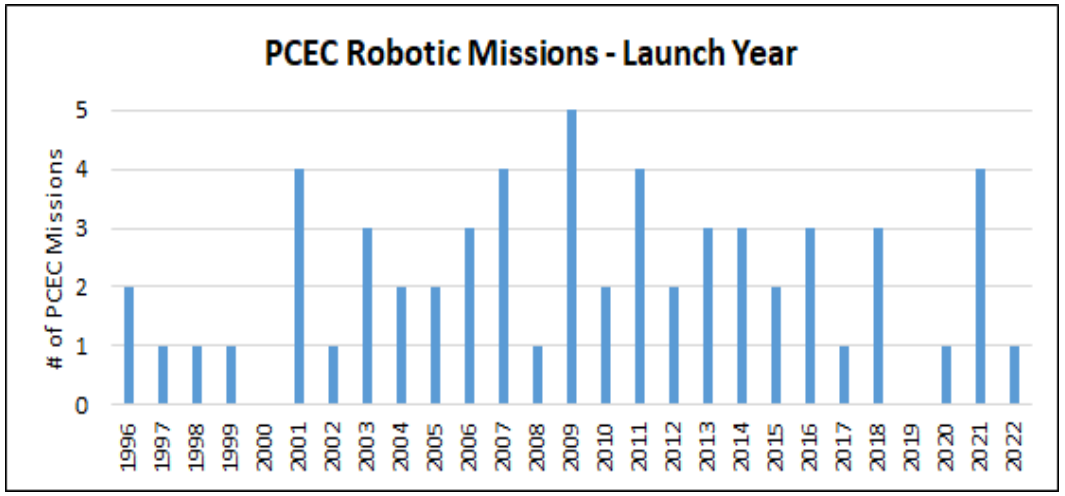
- Data includes 10 new missions available for the next version of PCEC CERs for Robotic Missions
- Updates include an expanded set of CER input candidates

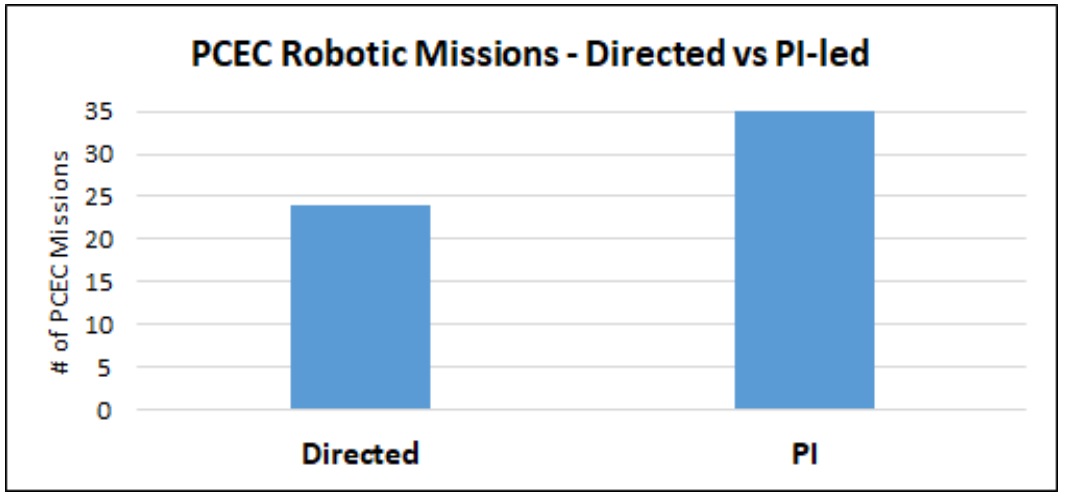
PCEC Robotic Mission Database - Statistics

- **Distributions of missions across SMD Division Launch Year, Risk Class, and Directed vs PI-led are shown here**







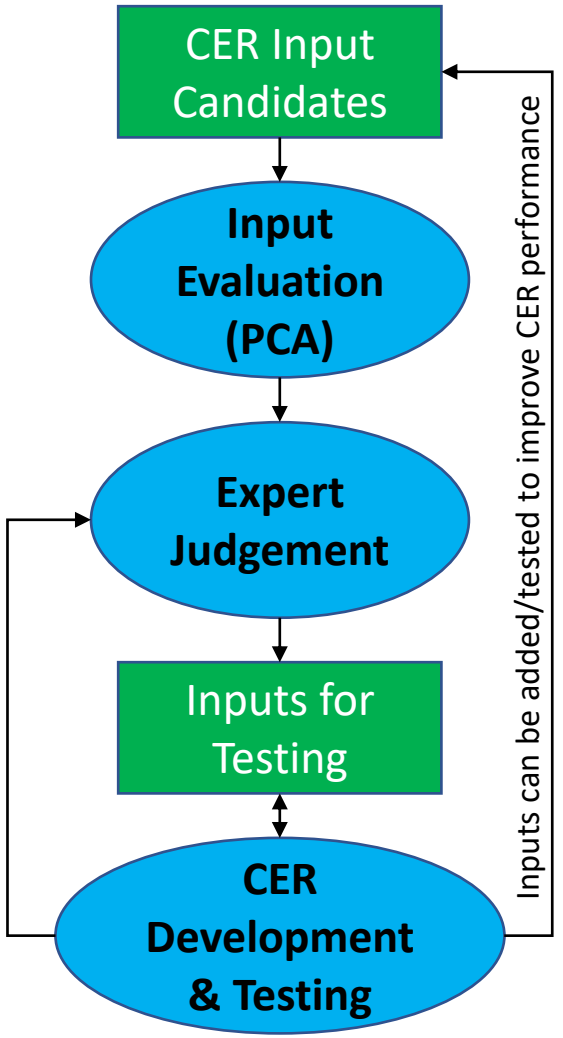


PCEC Robotic Mission CER Development Database

- PCEC's CER Development Database includes over 500 data fields for 70 flight elements including normalized costs & technical/schedule input candidates; Includes all data needed to run PCEC (& SOCM)
- CER development is an iterative process with significant identification and testing of new input candidates

PCEC CER DATABASE CONTENTS

	DEVELOPMENT DATA	OPERATIONS DATA
COST	Normalized Development Costs for S/C Subsystems and Project Support (Non-Recurring & Recurring)	Normalized Operations Costs for Cruise & Encounter (Planetary) or Prime & Extended (Earth)
TECHNICAL	S/C System and Subsystem Technical Characteristics (includes all PCEC CER inputs)	Mission Operations Technical Characteristics (includes all NASA SOCM inputs)
SCHEDULE	S/C Subsystem-specific Schedule	Cruise, Encounter, Prime, Extended Mission Operations Durations



PCEC CER Input Candidates, 1 of 3

INPUT CANDIDATES

GLOBAL	STRUCTURES	THERMAL
Mission Target/Type	STR Mass, kg	THM Mass, kg
Mission Risk Class	Radiation Environment, krads TID	Radiation Environment, krads TID
Power (EOL)	Number of Flight Elements	Project Lead Organization
Flight System Type	Primary Structure Material	THM Secondary, YorN
Environment	Flight SystemType	THM Heritage
No. of Flight Elements	Project Lead Org	THM Parts Rating
No. of Deployments	Operation Env	Environment
Progam	STR Secondary, YorN	Thermal Control Type
S/C Mass, kg	STR Heritage	Heater Power, W
	STR Parts Rating	Radiator Material
	No. of Articulated Devices	Project Lead Organization
	No. of Deployments	Thermal Control Type

Note: Schedule inputs are also considered including s/c subsystem Design, Fabrication, I&T, and Launch Ops; Cruise and Encounter times for Planetary operations; and Primary Mission duration for Near-Earth operations

PCEC CER Input Candidates, 2 of 3

INPUT CANDIDATES

PROPULSION	POWER	COMMUNICATIONS
PRP Mass, kg	Flight System Power, W BoL @1AU	TCM Mass, kg
Max Engine Thrust	Operating Environment	TCM Parts Rating
Tank Material	Number of Boards	Transmitter Power, W
Number of Thrusters	CDH Secondary, YorN	Band Type
Subsystem Heritage Rating	End of Life Power, W@1AU	TCM Secondary, YorN
PRP Secondary, YorN	CDH Mass, kg	TCM Heritage
PRP Heritage	CDH Heritage	U/L Band
PRP Parts Rating	CDH Parts Rating	Peak U/L Rate, kbps
Max Engine Thrust, N	Processor Type	D/L Band
Propulsion System Type	Data Storage Capacity, GB	Peak D/L Rate, Mbps
Tank Material	Operating Environment	Number of Bands
Propulsion System Type	Processor Type	Amp Type

Note: Schedule inputs are also considered including s/c subsystem Design, Fabrication, I&T, and Launch Ops; Cruise and Encounter times for Planetary operations; and Primary Mission duration for Near-Earth operations

PCEC CER Input Candidates, 3 of 3

INPUT CANDIDATES

GNC	POWER	OPERATIONS	
GNC Mass, kg	PWR Mass, kg	SOCM Level 1 Score	Data Storage Capacity, GB
Operating Environment	Operating Environment	Launch Date	U/L Band
Radiation Environment, krads TID	Radiation Environment	Flight System Type	Peak U/L Rate, kbps
GNC Subsystem Fab Time	End of Life Power, W@1AU	Mission Target/Type	D/L Band
Mission Target/Type (Robotic SC)	RTG, YorN	Mission Risk Class	Peak D/L Rate, Mbps
GNC Secondary, YorN	Harness Mass, %	Project Lead Organization	Daily D/L Volume, GB/day
GNC Heritage	PWR Secondary, YorN	S/C Lead Organization	
GNC Parts Rating	PWR Heritage	S/C Lead Experience	
GN&C Type	PWR Parts Rating	Mass	
Pointing Accuracy, arcsecs	BOL Power @ 1 AU	Power (EOL)	
Pointing Knowledge, arcsecs	Solar Array Area, m2	Heritage	
GNC Type2	Avg Payload Power, W	Parts Rating	
Operating Environment	Battery Capacity, Ahrs	# of Flight Elements	
Mission Target/Type (Robotic SC)	Harness Mass, kg	Operating Environment	
GN&C Type	Avg Operating Power, W	Radiation Environment	

Note: Schedule inputs are also considered including s/c subsystem Design, Fabrication, I&T, and Launch Ops; Cruise and Encounter times for Planetary operations; and Primary Mission duration for Near-Earth operations

Normalization Change for Mars Landed Missions

***Issue*: Allocations of cost to individual flight elements has been entirely mass-based**

Mars Landed Mission Flight Elements → CRUISE STAGE | ENTRY SYSTEM | LANDER/ROVER

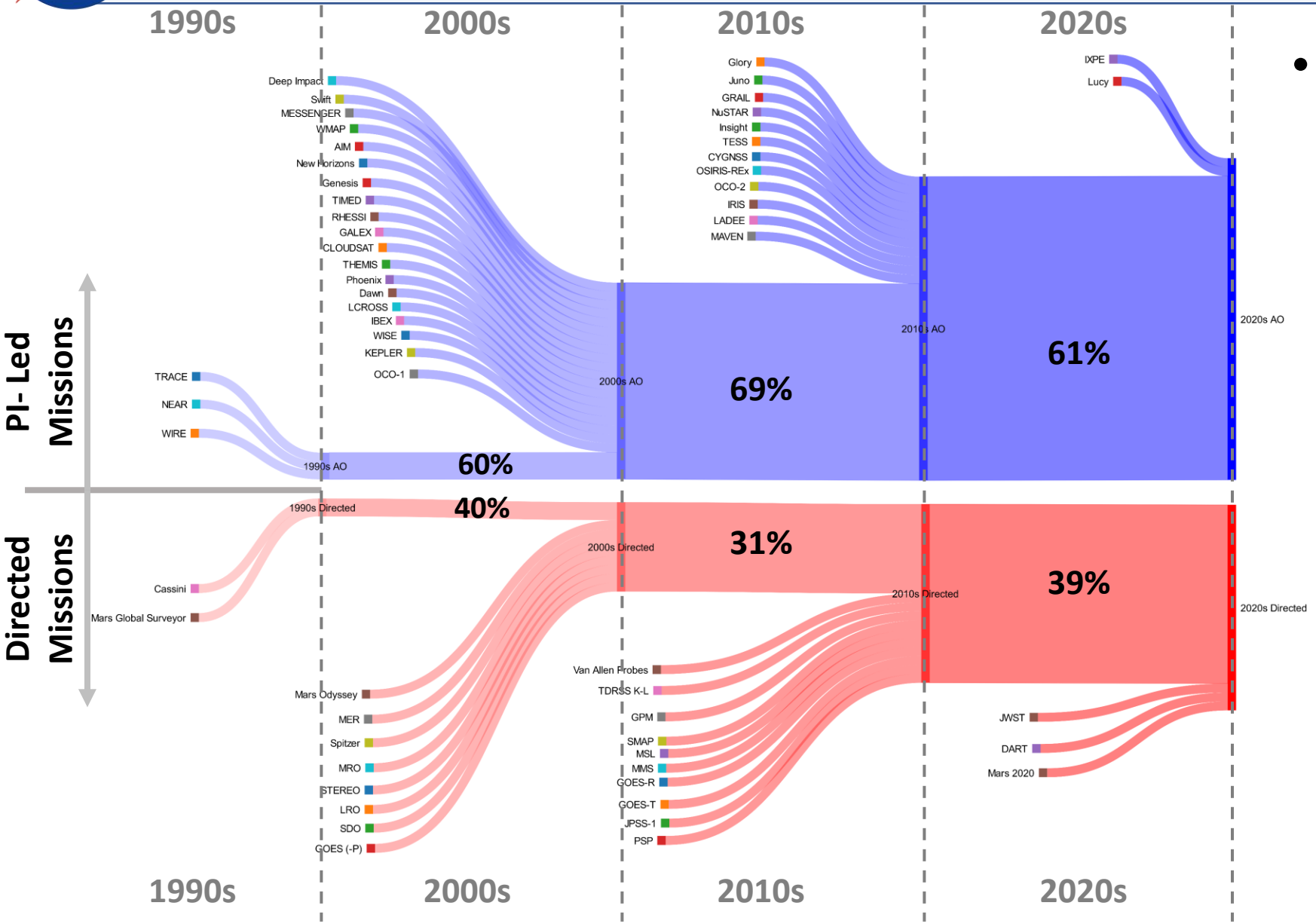
- **Since the hardware providing the primary capability for the Cruise Stage and Entry System typically reside within the Lander/Rover, this approach over-costs these elements and under-costs the Lander/Rover**
- **Adjustments have been applied to the mass-based approach**
  - Adjustments performed at the subsystem level
  - Two adjustments: Subsystem inputs include Reliance on External Hardware (Y/N) and Heritage (assessed relative to Lander/Rover)
- **Initial CER development demonstrated the revised normalization approach reduced the number of outliers for the s/c subsystem CERs**
  - This is the approach used for PCEC v2.4 CERs
  - *Impacted Projects*: InSight, MER, MSL, and Mars 2020

Separation of MO & DA for PCEC Phase E CERs

- **To provide enhanced insight into Phase E costs, separate CERs for Mission Operations and Data Analysis were developed but not yet adopted**
  - CERs cover Planetary Cruise & Encounter phases and Near-Earth Primary Mission

Mission Operations (MO)	NASA WBS	Data Analysis (DA)
Next level of detail needed to separate engineering from science	1 Project Management	
	2 Systems Engineering	
	3 Mission Assurance	
	4 Science Team	Science Team efforts include EPO; Payload only included if Science Team book-kept in WBS 5
Next level of detail needed to separate engineering from science for WBS 7; Typically, no post-launch S/C $s	5 Payload	
	6 Spacecraft	
	7 Mission Operations System	
	8 Launch Vehicle	
	9 Ground Data System	Next level of detail needed to separate engineering from science
Typically, no post-launch I&T $s	10 I&T	

Directed/Pi-Led History by Mission Launch Year



- **Mission data mix in the PCEC database has evolved over time**
  - During PCEC v2.3 CER development, the database contained a higher percentage of PI-Led missions (69%) when compared to Directed missions (31%)
  - Today, with the addition of new data points, the gap narrowed (61% vs. 39%)
  - This change in the data mix has introduced some challenges in the development of new CERs

PCEC v2.4 Outlier Summary

Identified Outliers By CER		GOES-R	Cassini	JWST	MSL-Rover	Mars 2020 - Rover	TDRSS K-L	PSP	MESSENGER	MSL-EDL	JPSS-1	Spitzer	GOES (-P)	GOES-T	GPM	Mars 2020 - EDL	Van Allen Probes	Juno	LRO	MER - EDL	MRO	MSL-Cruise Stage	SDO	STEREO	MAVEN	MER - Rover	NEAR	New Horizons	WMAP
Spacecraft Subsystems	STR NRC	X	X	X	X	X		X		X						X				X									
	STR RC		X	X	X	X				X						X				X									
	THM NRC			X	X			X								X						X							
	THM RC	X	X		X			X											X			X	X						X
	PRP NRC	X	X	X					X	X						X											X		
	PRP RC	X	X	X						X				X														X	
	CDH NRC	X	X	X	X																								
	CDH RC	X	X		X							X																	
	TCM NRC	X	X	X	X		X	X	X												X								
	TCM RC	X	X				X				X																		
	GNC NRC	X	X							X					X														
	GNC RC	X	X	X						X			X		X								X						
	PWR NRC	X	X	X			X	X									X												
	PWR RC	X	X	X	X										X														
Support Function	PM-Tot	X		X							X		X																
	SE-Tot	X	X	X	X	X					X		X																
	MA-Tot	X	X	X	X	X	X				X		X					X								X			
	landT-To	X		X	X	X	X																						
Phase E	MODA TOT	X		X								X		X	X		X							X					

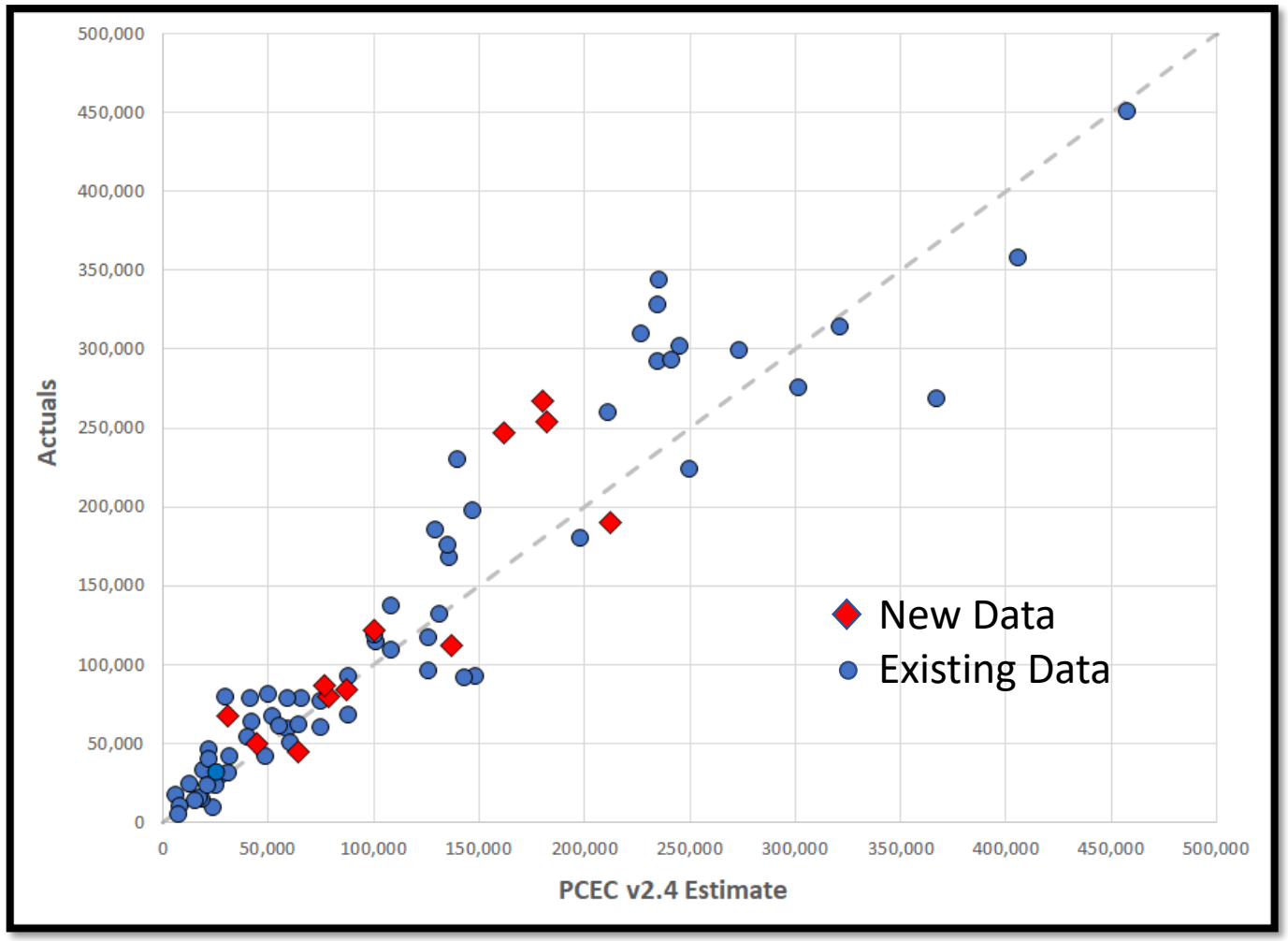
- **Inclusion of several new directed/flagship type missions in the PCEC database has shifted the CER trade space**
  - JWST, Cassini, GOES-R and the newest Mars rovers are the worst outliers across most of the CER categories due to their high degree of complexity not seen in most other SMD missions in the PCEC database
  - Several missions that were considered to be outliers in PCEC v2.3 are now included in the new CERs (e.g. TDRSS K-L, GPM)

CER Performance Comparison

PCEC Performance Comparison			RMSE		# of Data Points	
			PCEC v2.3	*PCEC v2.4*	*PCEC v2.3*	*PCEC v2.4*
Support Functions (Phase B-D)		Total Project Management	251	265	47	53
		Total Systems Engineering	254	164	47	48
		Total Mission Assurance	111	113	41	43
		Total Integration & Test	753	863	43	48
Spacecraft Subsystems (Phase B-D)	Non-Recurring	Structures & Mechanisms	2,279	4,529	50	60
		Propulsion	2,672	2,149	40	45
		Telecommunications	2,700	2,520	49	58
		Guidance, Navigation and Control	2,870	3,319	51	63
		Thermal	484	722	52	63
		Command & Data Handling	5,322	4,950	44	57
		Power	3,396	4,532	43	62
	Recurring	Structures & Mechanisms	5,710	11,226	51	62
		Propulsion	4,069	4,064	38	46
		Telecommunications	5,847	5,782	52	63
		Guidance, Navigation and Control	4,235	5,535	49	60
		Thermal	1,197	1,970	50	62
		Command & Data Handling	8,508	6,585	44	58
		Power	5,221	5,568	45	64
Mission Operations (Phase E)		Mission Operations & Data Analysis	699	1,977	38	42
		CER Performance as good as or better than v2.3				

- **PCEC v2.4 CER performance is the same or better for many of the newly developed CERs when compared to PCEC v2.3**
  - In the cases where performance trended down, there is a significant increase in the number of data points informing the CER
  - In these cases, the number of data points increased 20% on average and ultimately made the CERs more inclusive of the entire SMD portfolio
  - Several missions that were considered to be outliers in PCEC v2.3 are now included in the new CERs

Visualization of PCEC v2.4 Performance



NOTE: Development costs do not include Payload (WBS 5) or Launch Vehicle (WBS 8), Science Team (WBS 4) Phase F or Pre-Launch MOS_GDS (WBS 7/9)

- **The preliminary PCEC v2.4 spacecraft model is performing as expected**
  - The updated model at the mission level appears to be generating results on par or better than v2.3
  - Red diamonds highlight the new missions added to the PCEC database (e.g. TESS, GOES-T, PSP)
  - Although not shown here, JWST has the highest error which is expected given the uniqueness and complexities of this mission

Future Plans

- **Finalize v2.4 spacecraft CERs in preparation for the next PCEC release which is scheduled for late 2024**
  - Update PCEC whitepaper to reflect updates to the modeling process and document relevant results
- **Further investigation of Phase E/F CERs is needed**
  - Re-examine Mission Operations & Data Analysis CERs in an attempt to find an approach that better captures Mission Operations and Data Analysis as separate CERs
- **Re-visit pre-launch MOS/GDS and Science CERs**
  - Explore alternate scenarios that may better identify drivers of these costs
- **Improve database storage and manipulation using commercial solutions such as those offered by Amazon Web Services (AWS)**
  - Although widely used across NASA, recent events may prohibit the use of a third party solution

Importance of CADRe

- CADRe is the “Pot of Gold” for programmatic analysts at the end of each critical phase
- When funding is tight, it is even more important to collect programmatic data to improve prediction capabilities
- PCEC (and other tools) would not be possible without availability of CADRe