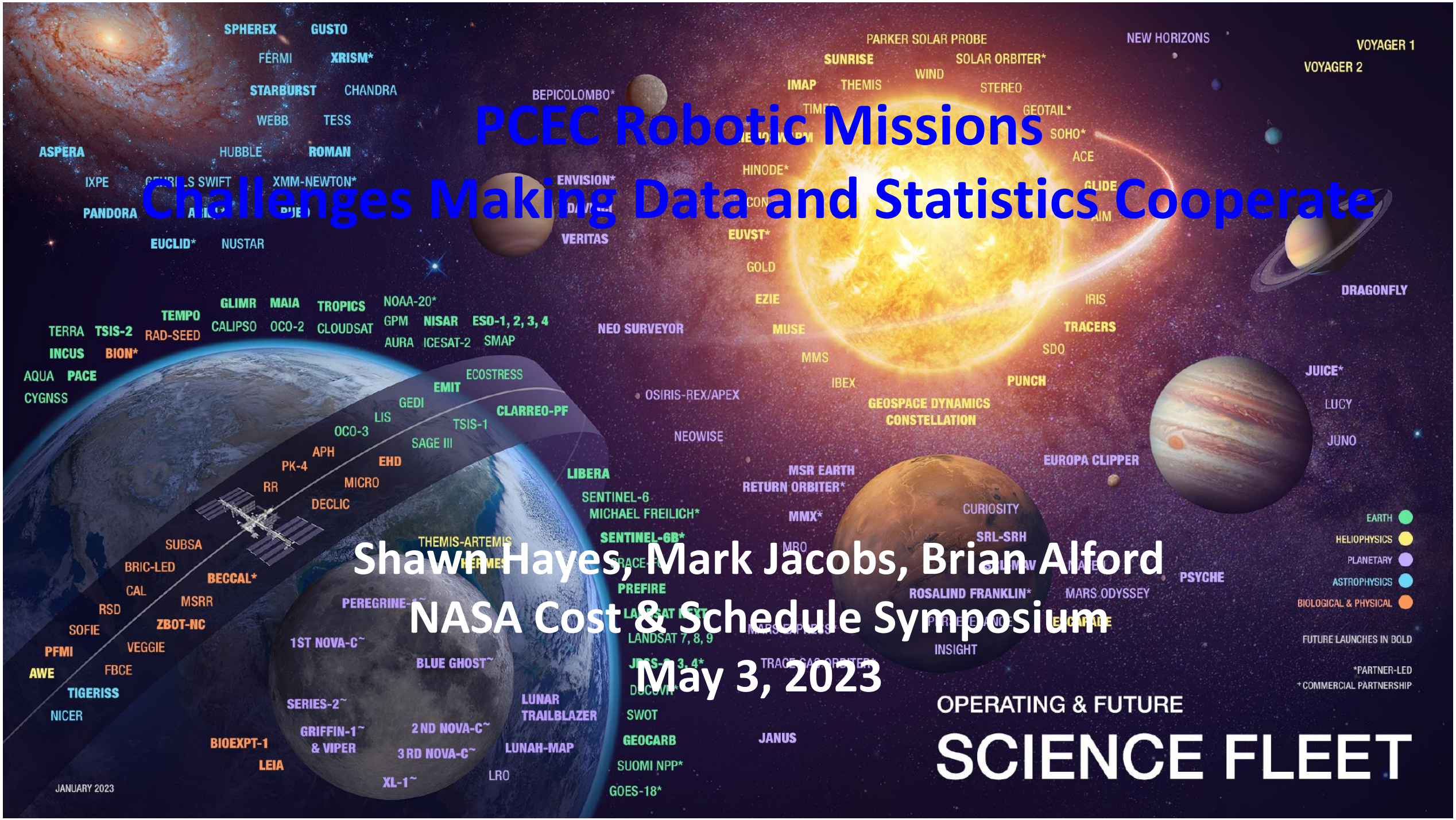

PCEC Robotic Missions
Challenges Making Data and Statistics Cooperate
Shawn Hayes, Mark Jacobs, Brian Alford
NASA Cost & Schedule Symposium
May 3, 2023
OPERATING & FUTURE
SCIENCE FLEET
JANUARY 2023
FUTURE LAUNCHES IN BOLD
*PARTNER-LED
+COMMERCIAL PARTNERSHIP
EARTH
HELIOPHYSICS
PLANETARY
ASTROPHYSICS
BIOLOGICAL & PHYSICAL
SPHEREX
GUSTO
FERMI
XRISM*
STARBURST
CHANDRA
WEBB
TESS
ASPERA
HUBBLE
ROMAN
IXPE
NEIL GEHRELS SWIFT
XMM-NEWTON*
PANDORA
EUCLID*
NUSTAR
PARKER SOLAR PROBE
NEW HORIZONS
VOYAGER 1
VOYAGER 2
SUNRISE
SOLAR ORBITER*
WIND
IMAP
THEMIS
STEREO
BEPICOLOMBO*
GEOTAIL*
SOHO*
ACE
HINODE*
ENVISION*
GLIDE
VERITAS
EUVST*
GOLD
EZIE
IRIS
DRAGONFLY
TEMPO
GLIMR
MAIA
TROPICS
NOAA-20*
TERRA
TSIS-2
RAD-SEED
CALIPSO
OCO-2
CLOUDSAT
GPM
NISAR
ESO-1, 2, 3, 4
AURA
ICESAT-2
SMAP
NEO SURVEYOR
MUSE
TRACERS
INCUS
BION*
SDO
AQUA
PACE
ECOSTRESS
EMIT
IBEX
PUNCH
JUICE*
CYGNSS
GEDI
OSIRIS-REX/APEX
LUCY
LIS
CLARREO-PF
GEOSPACE DYNAMICS
CONSTELLATION
OCO-3
TSIS-1
JUNO
NEOWISE
SAGE III
APH
EHD
EUROPA CLIPPER
PK-4
RR
MICRO
LIBERA
MSR EARTH
RETURN ORBITER*
DECLIC
SENTINEL-6
CURIOSITY
MICHAEL FREILICH*
MMX*
SUBSA
SENTINEL-6B*
SRL-SRH
THEMIS-ARTEMIS
MRO
BRIC-LED
BECCAL*
PSYCHE
PREFIRE
ROSALIND FRANKLIN*
CAL
MSRR
MARS ODYSSEY
PEREGRINE-1~
RSD
ZBOT-NC
LANDSAT 7, 8, 9
SOFIE
1ST NOVA-C~
VEGGIE
INSIGHT
PFMI
BLUE GHOST~
FBCE
AWE
SERIES-2~
LUNAR
TRAILBLAZER
TIGERISS
SWOT
NICER
GRIFFIN-1~
& VIPER
2 ND NOVA-C~
BIOEXPT-1
3 RD NOVA-C~
LUNAH-MAP
GEOCARB
JANUS
LEIA
SUOMI NPP*
XL-1~
LRO
GOES-18*

PCEC – Challenges Making Data and Statistics Cooperate

OUTLINE

1. PCEC Robotic Mission Database

- 10 new missions since v2.3
- Robotic Mission CER Development Database

2. Data Collection & Normalization Challenges

- COVID Impacts = “New Normal”? (Supply Chain, Staffing, Schedule)
- Keeping up with Inflation
- Data limitations from FFP
- Limitations for Allocating Costs to Multiple Flight Elements (Mars landed missions)

3. CER Development Challenges

- Data analysis alternatives (Classification and Regression Tree analyses)
- Tailored CERs (improvements for “flagship-class” missions)
- Figures-of-Merit (addresses input deficiencies and payload accommodations complexity)
- Improving on performance of v2.3 CERs

4. Future Plans

PCEC Robotic Mission Database

- Database covers 59 missions and 70 separate flight elements

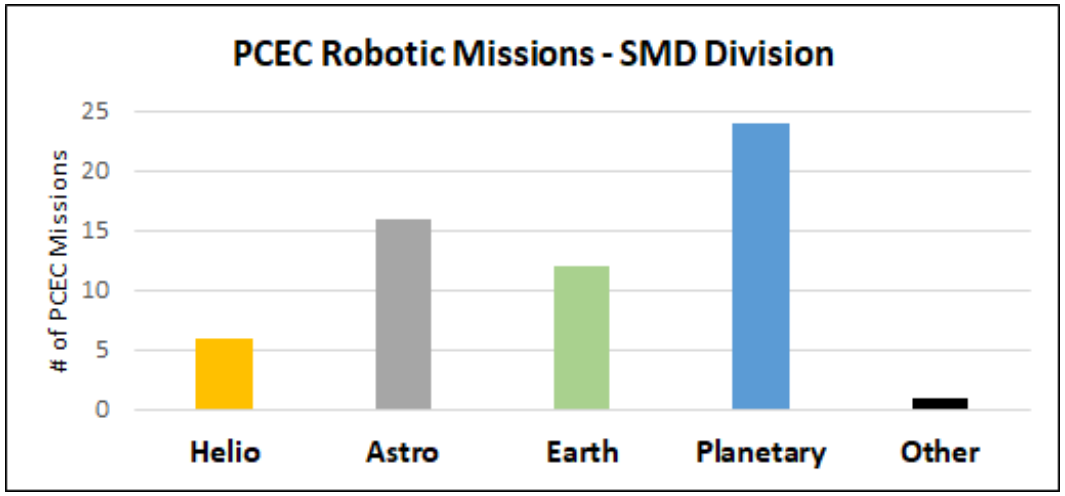
MISSION	Launch Date	Lead Org PM	Lead Org Flt Sys	NASA Program	Mission Risk Class
Missions for PCEC v2.3					
1 TDRSS K-L	1/23/14	GSFC	Boeing	Space Comm	Class A
2 MAVEN	11/18/13	GSFC	LMA	Planetary	Class C/D
3 LADEE	9/6/13	GSFC	ARC	Planetary	Class B
4 IRIS	6/27/13	GSFC	LMMS	Astrophysics/SMEX	Class C/D
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

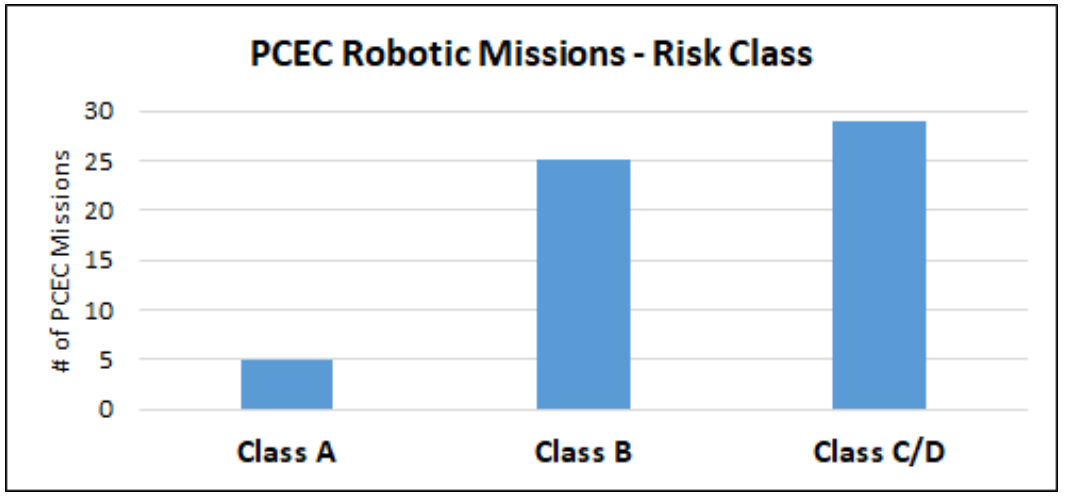
MISSION	Launch Date	Lead Org PM	Lead Org Flt Sys	NASA Program	Mission Risk Class
New Missions with Normalized Data					
50 SMAP	1/31/15	JPL	JPL	Earth Sciences	Class C/D
51 JPSS-1	11/10/17	GSFC	BATC	Earth Sciences	Class B
52 Solar Probe	8/6/18	GSFC	APL	Heliophysics	Class B
53 Mars 2020	7/30/20	JPL	JPL	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

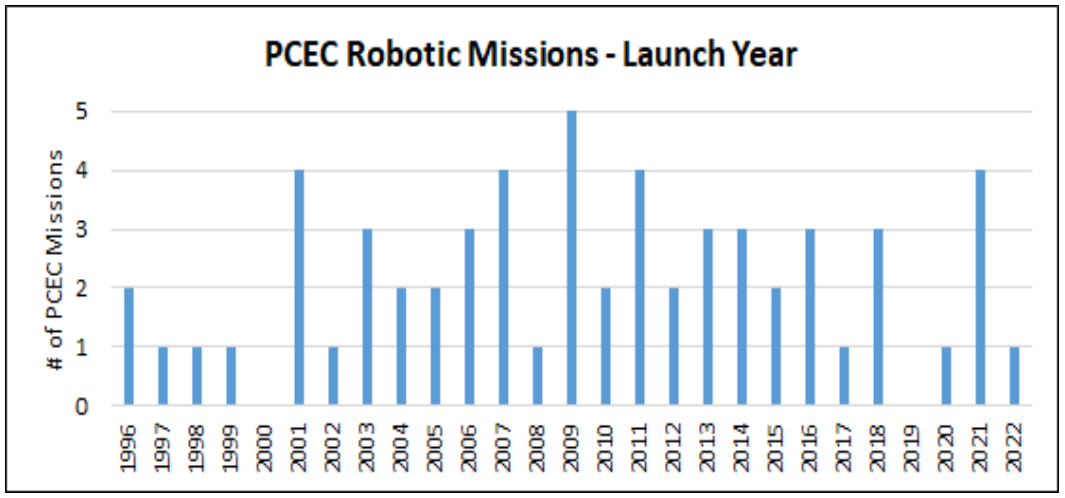
- Data includes 10 new missions available for the next version of PCEC CERs for Robotic Missions

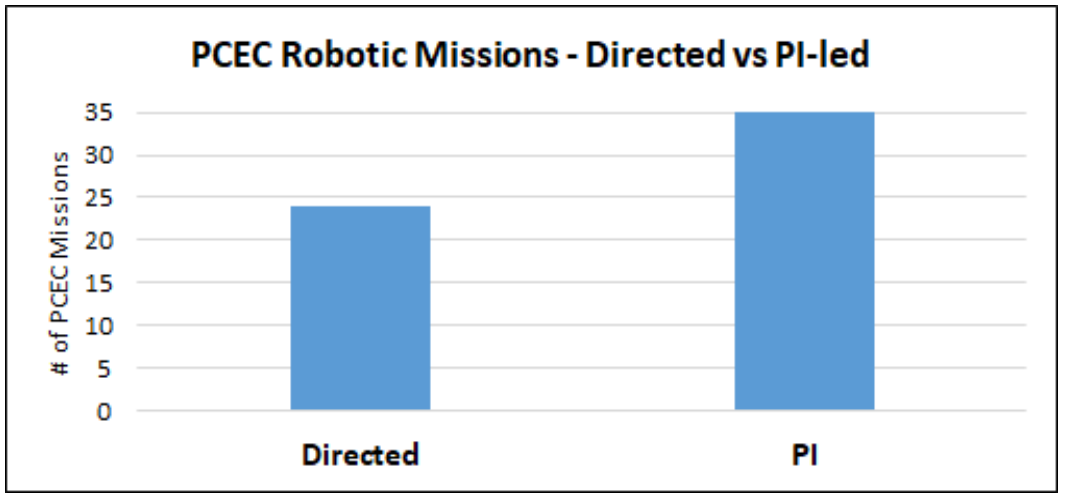
PCEC Robotic Mission Database - Statistics

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







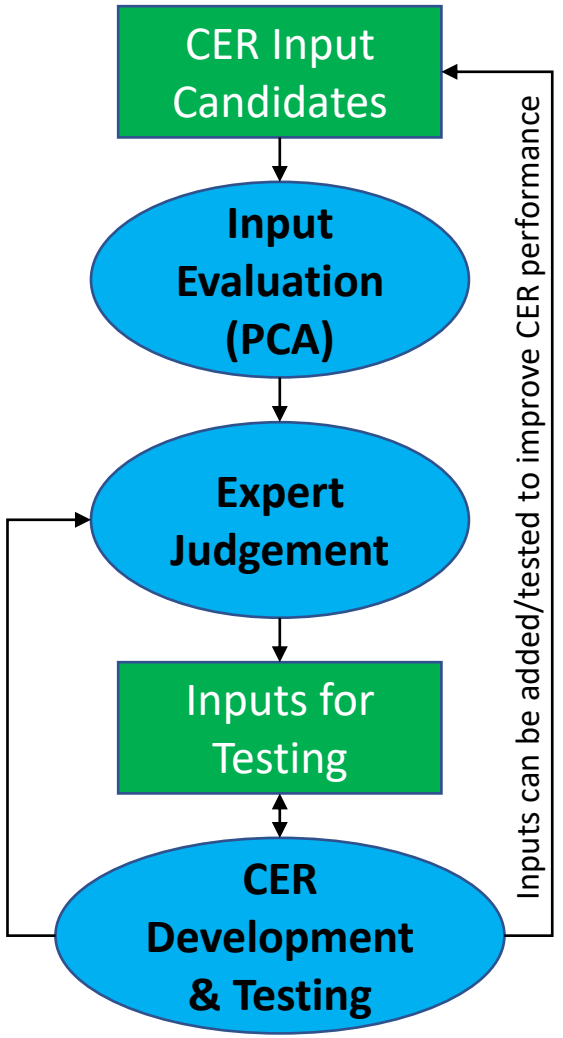


PCEC Robotic Mission CER Development Database

- 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



Data Collection & Normalization Challenges

COVID

- Includes Supply Chain, Staffing, and Schedule

Inflation

- Significant recent growth; NASA inflation factors seem somewhat optimistic

Contract Limitations (FFP)

- Savings often come with associated data visibility limitations

Allocating Costs to Multiple Flight Elements

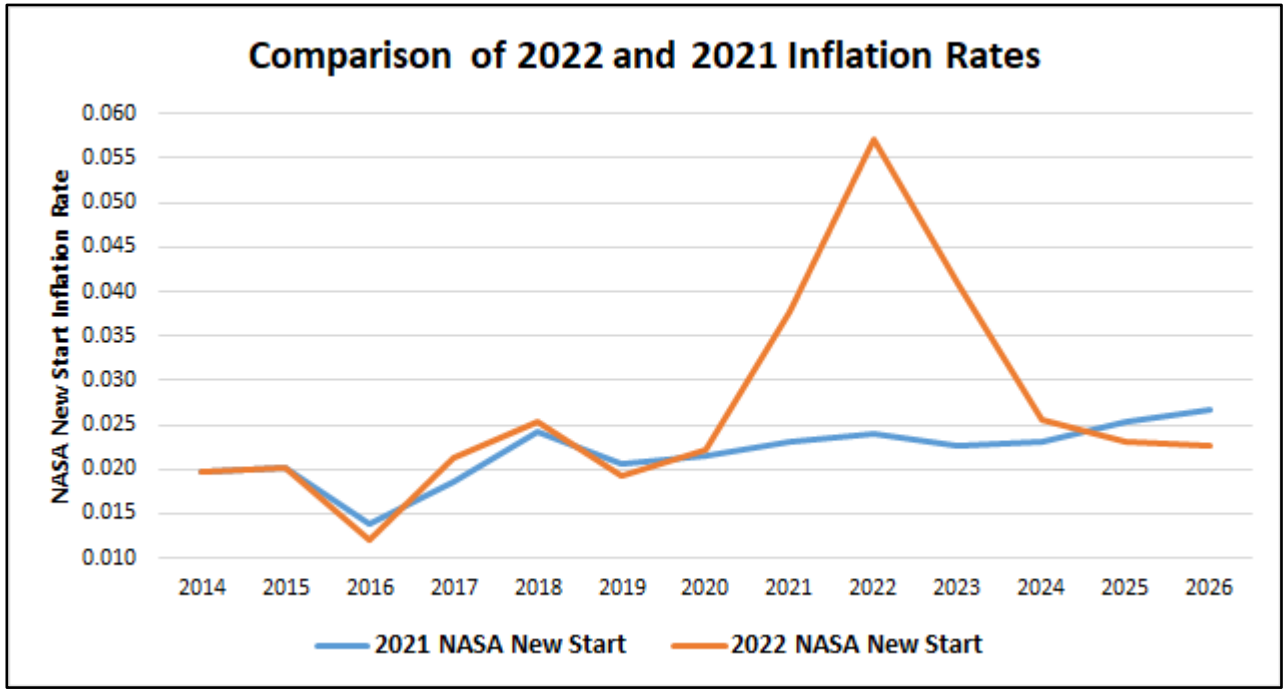
- Difficulty splitting costs for Cruise Stages, Entry Systems, and Landers/Rovers; Applies to most Mars landed missions

Data Collection & Normalization Challenges - COVID

- **COVID-related impacts include issues associated with Supply Chains, Staffing, and Schedule**
  - Supply Chain issues existed pre-COVID but have been amplified
- **Significant impacts realized from March 2020 through late 2022**
  - PCEC missions affected: IXPE, Dart, JWST, Lucy
  - Impacts averaged ~5% growth during this period
  - Some projects had significantly higher/lower growth
- **Although not explicitly recognized as "COVID-related", issues with Supply Chains, Staffing, and Schedule continue**
  - These issues seem common across many (or all?) current projects
- **PCEC Challenge: Continue to normalize-out COVID impacts or include to cover the "new" normal experience?**
  - Leaning toward including these costs in the normalized data

Data Collection & Normalization Challenges - INFLATION

- **Latest version of NASA New Start Inflation rates reflect a significant increase for 2021-2023**
  - Peak of 5.7% in 2023 seems low
- **Assumption is reductions will be realized after 2023**
  - Not likely realistic; Could significantly impact Phase E RY estimates



Data Collection & Normalization Challenges - CONTRACTS

- **Some projects do not provide subsystem-level breakouts for s/c subsystems**
  - Due to limitations from Firm Fixed Price arrangements
  - Additional effort (thank you Eric P!) has provided breakouts for some projects
- **Three PCEC candidate projects are currently affected**
  - CADRes exist for ICESat-2, ICON, and TROPICS, but s/c subsystem-level breakouts are not available
- **Efforts should be made to attempt collection of subsystem-level data for future FFP contracts**
  - Although this may come at some cost, the value of the data is high
  - Much more difficult to get this split after launch – Best to get the breakdown as early as possible in a project's lifecycle

Data Collection & Normalization Challenges - MULTIPLE ELEMENTS

- **Costs for Cruise Stages, Entry Systems, and Landers/Rovers are not explicitly captured in project accounting systems**
  - Affects Mars landed projects: MER, MSL, InSight, and Mars 2020
  - Guidance suggested using mass distributions as representative of cost distributions
  - This approach seems oversimplistic and results in higher-than-expected costs for Cruise Stages (typically high-heritage) and Entry Systems (high mass but lower $/kg) and lower-than-expected costs for Landers/Rovers
- **Alternative allocation approaches are under study**
  - Subsystem-level factors have been developed to capture heritage, $/kg, and whether a subsystem is using significant Lander/Rover elements
  - The intention is to conduct PCA on the unadjusted and adjusted data sets to see if there is any reduction in number of outliers (which often included the affected projects)

CER Development Challenges

Data Analysis Alternatives

- Leveraging findings from Classification & Regression Tree (CART) Analysis

Tailored CERs

- Difficult to determine best way to split the data set (many options)

Figures-of-Merit

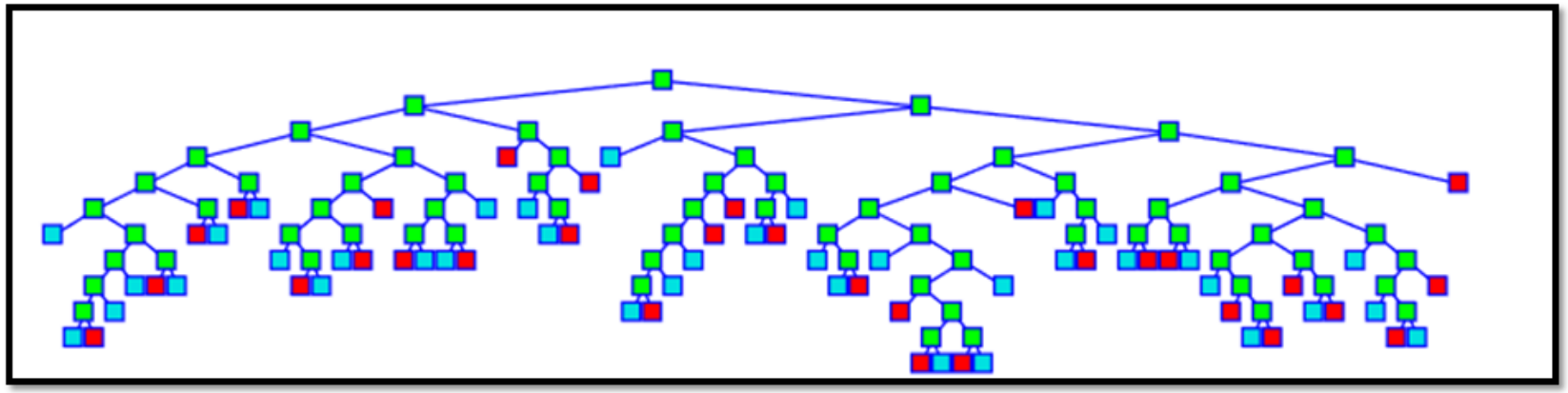
- Beginning to explore options for using FoMs with initial efforts focusing on a payload accommodations complexity metric

Improving on PCEC v2.3 CERs

- Many alternatives have been explored but have not shown improvement over the current CERs

Introduction to CART Analysis

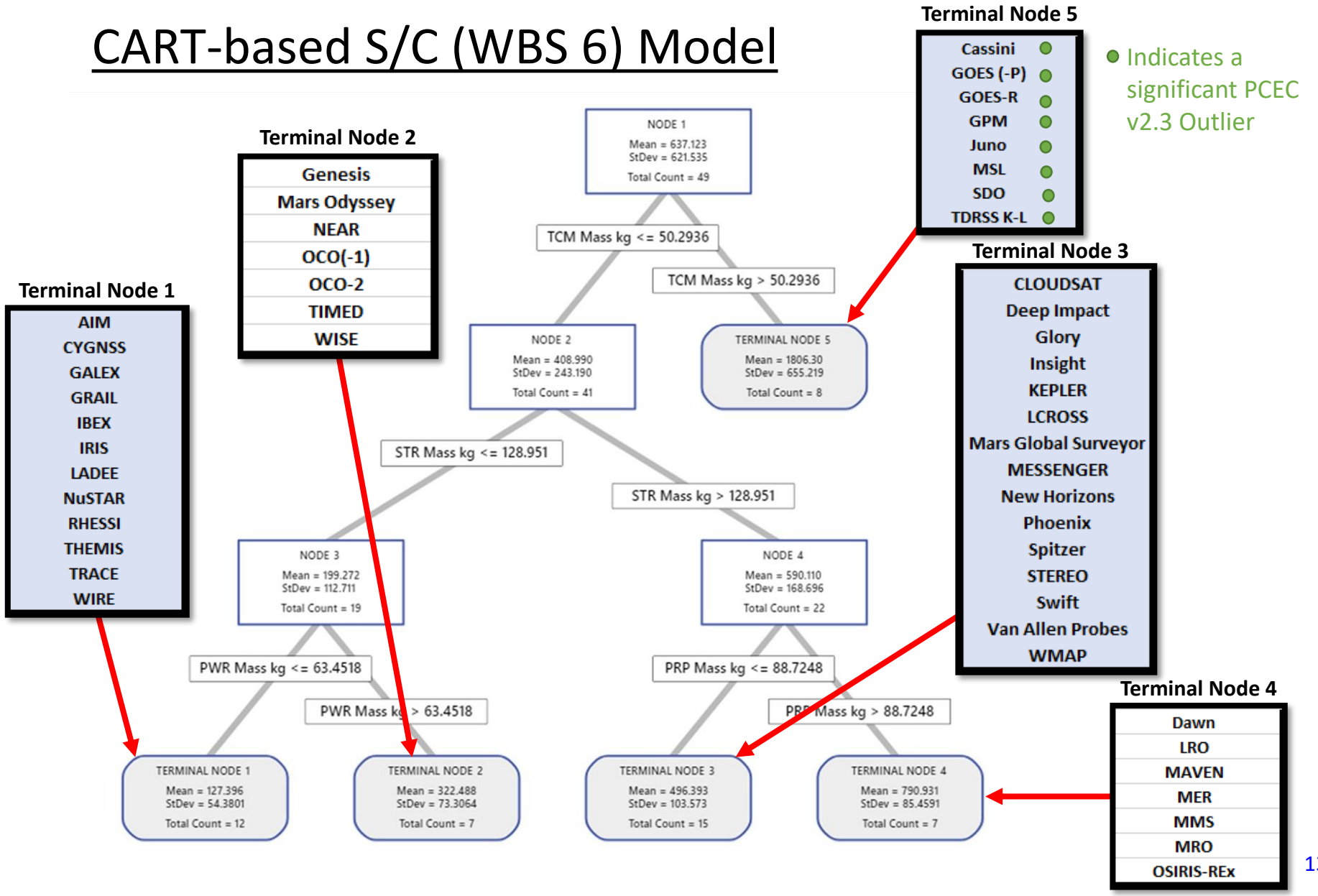
- Classification and Regression Tree (CART) analysis is a tree-based method which uses a recursive partitioning method to build regression trees for predicting continuous dependent variables.
- In CART, each non-terminal node (green square) identifies a split condition or branch, to yield optimum prediction in the response variable. Each terminal node or leaf (blue/red squares) provides a mean estimate based on prior decisions.
- CART provides predictive models with high accuracy, stability and ease of interpretation. Unlike linear models, they map non-linear relationships quite well and do not require database pre-processing for missing values, removal of outliers or log transformation of the data set.



CER Development Challenges – Data Analysis Alternatives

- This example CART S/C CER allocated 8 projects that were often outliers for the v2.3 to a single node
- Performance varies by node but has greater error than the v2.3 CERs
- Nodes identified from this analysis are under investigation as CER input candidates (depending on PCA analysis results)

CART-based S/C (WBS 6) Model

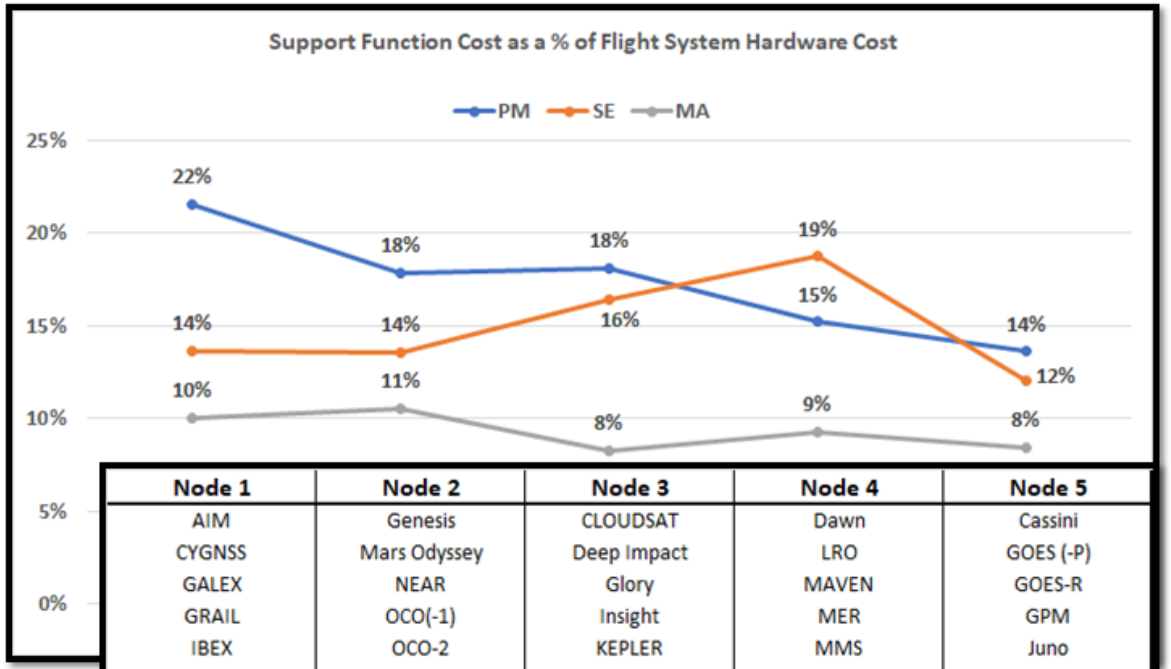


CER Development Challenges – Data Analysis Alternatives

CART-based Support Function Model

- A support function model that utilizes historical wrap factor data categorized by the CART spacecraft model node classifications was developed
- Although the CART based support function model could not compete with the performance of the PCEC v2.3 CERs, an interesting observation was made
- As mission complexity increases, the PM/MA costs as a percentage of flight system hardware costs decrease
  - Implies that a fixed level or floor of PM/MA effort is needed regardless of the complexity level of hardware being built

Inputs	
Spacecraft ***Communications*** *Subsystem Mass w/ Contingency (kg)*	4.3
Spacecraft ***Structures & Mechanisms*** *Subsystem Mass w/ Contingency (kg)*	54
Spacecraft ***Power*** *Subsystem Mass w/ Contingency (kg)*	43.5
Spacecraft ***Propulsion*** *Subsystem Mass w/ Contingency (kg)*	0
Payload *Cost Estimate ($K)*	$40,246
Spacecraft *Cost Estimate ($K)*	$23,544



Node 1	Node 2	Node 3	Node 4	Node 5
AIM	Genesis	CLOUDSAT	Dawn	Cassini
CYGNSS	Mars Odyssey	Deep Impact	LRO	GOES (-P)
GALEX	NEAR	Glory	MAVEN	GOES-R
GRAIL	OCO(-1)	Insight	MER	GPM
IBEX	OCO-2	KEPLER	MMS	Juno
IRIS	TIMED	LCROSS	MRO	MSL
LADEE	WISE	Mars Global Surveyor	OSIRIS-REx	SDO
NuSTAR		MESSENGER		TDRSS K-L
RHESSI		New Horizons		
THEMIS		Phoenix		
TRACE		Spitzer		
WIRE		STEREO		
		Swift		
		Van Allen Probes		
		WMAP		

CER Development Challenges – Figures-of-Merit

PCEC Payload Accommodations Database

- PCEC input candidates include several Payload inputs: Total Mass, Total Power, # of Instruments
- These inputs do not seem to adequately capture complexity of supporting the payload for I&T and other Project Support functions
- Additional Payload characteristics may better capture Accommodations complexity
- Enhanced insight into Payload Accommodations impacts on I&T, PM/SE/MA, and MOS/GDS development could improve PCEC CER performance

Mass	Power	Volume
- Individual Instruments - Total Mass	- Individual Instruments - Total Power	- Individual Instruments - Total Volume

Thermal	Data Rate	Pointing
- Instr-specific Min Op T - Lowest Op T	- Individual Instruments - Total Data Rate	- Individual Instruments - Most Precise Reqt

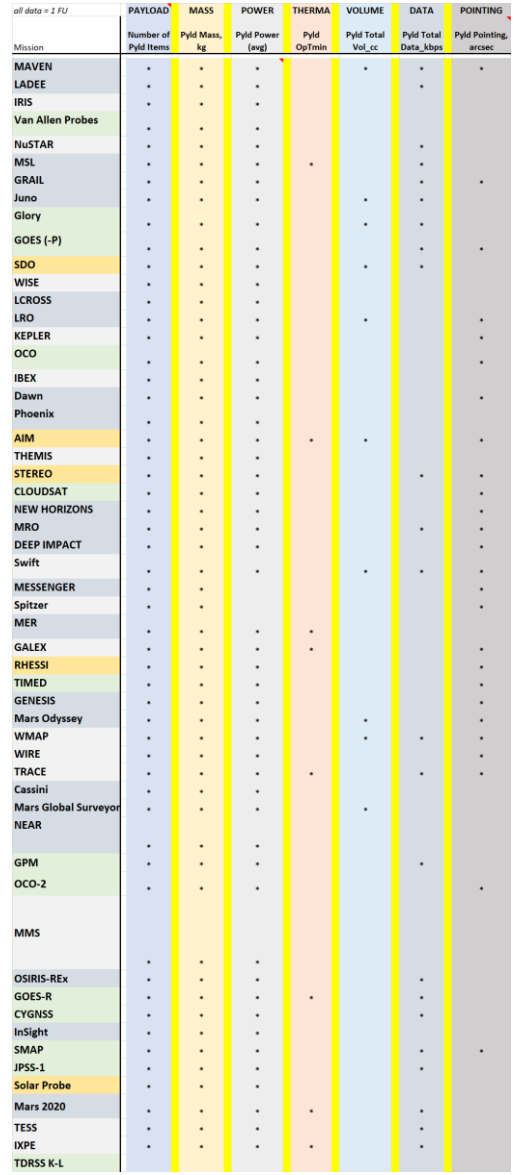
CER Development Challenges – Figures-of-Merit

PCEC Payload Accommodations Database Status

- **Data mining efforts underway to find missing metrics**
  - Requires use of CADRe supporting documentation
  - Effort is taking more time than expected, so a higher-level approach has been explored

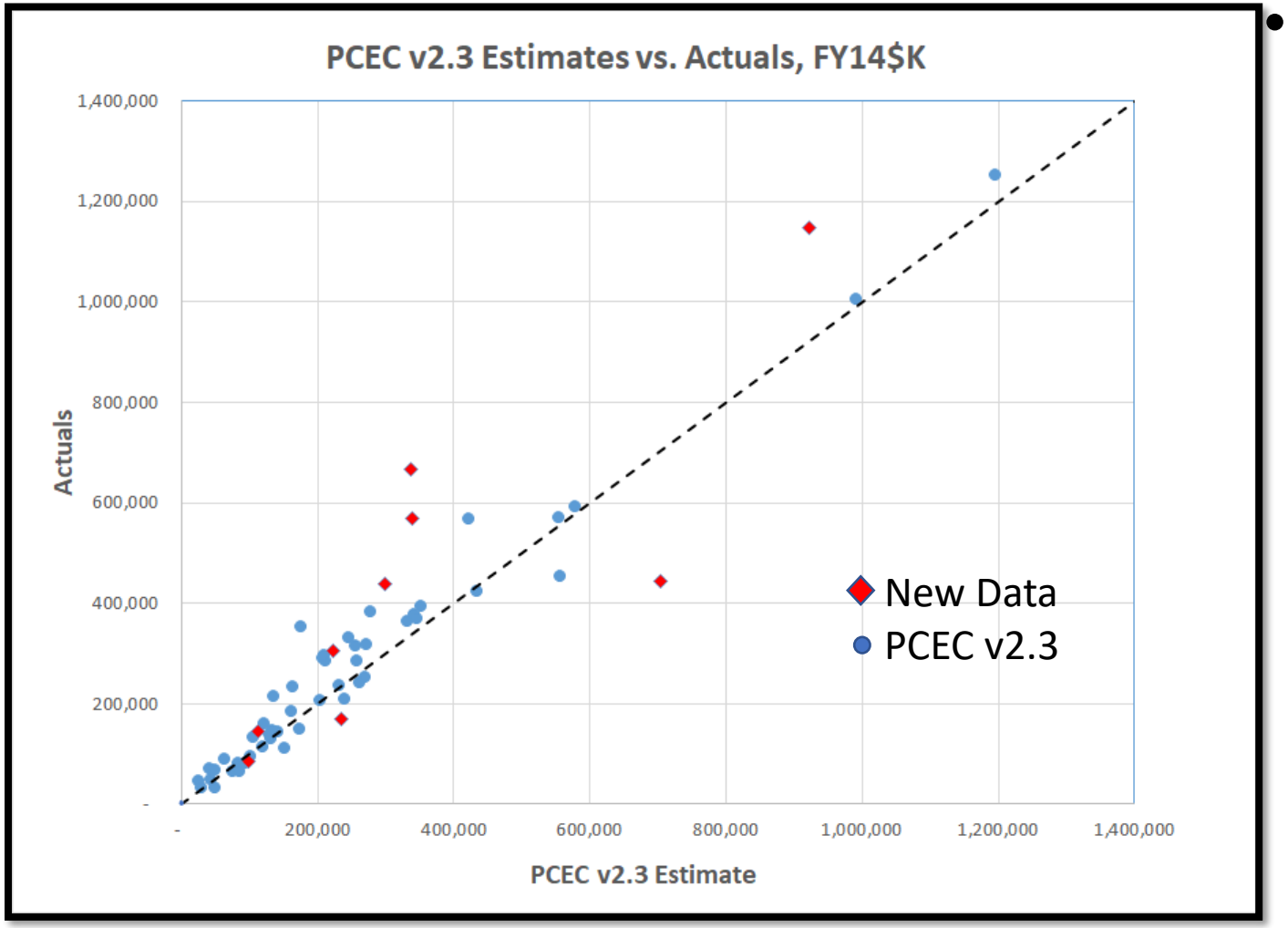
- **Using higher-level inputs to capture some performance metrics**
  - ***Pointing***: Using overall s/c pointing reqts vs individual instruments
  - ***Thermal***: Assign thermal design classifications vs using individual instrument Op Temps
  - ***Data Rate***: Using overall Science Data D/L volume (GB/day)
  - Categories may be used to characterize each of these metrics

- **Develop Payload Accommodations Complexity Estimator**
  - Use collected data to derive a Figure-of-Merit representing accommodations complexity
  - Explore deriving accommodations complexity estimates for individual instruments and total payload



all data = 1 FU	PAYLOAD	MASS	POWER	THERMA	VOLUME	DATA	POINTING
Mission	Number of Pyld Items	Pyld Mass, kg	Pyld Power (avg)	Pyld OpTmin	Pyld Total Vol_cc	Pyld Total Data_kbps	Pyld Pointing, arcsec
MAVEN	•	•	•		•	•	•
LADEE	•	•	•			•	
IRIS	•	•	•				
Van Allen Probes	•	•	•				
NuSTAR	•	•	•			•	
MSL	•	•	•	•		•	
GRAIL	•	•	•			•	•
Juno	•	•	•		•	•	
Glory	•	•	•		•	•	
GOES (-P)	•	•	•			•	•
SDO	•	•	•		•	•	
WISE	•	•	•				
LCROSS	•	•	•				
LRO	•	•	•		•		•
KEPLER	•	•	•				•
OCO	•	•	•				•
IBEX	•	•	•				
Dawn	•	•	•				•
Phoenix	•	•	•				
AIM	•	•	•	•	•		•
THEMIS	•	•	•				
STEREO	•	•	•			•	•
CLOUDSAT	•	•	•				•
NEW HORIZONS	•	•	•				•
MRO	•	•	•			•	•
DEEP IMPACT	•	•	•				•
Swift	•	•	•		•	•	•
MESSENGER	•	•					•
Spitzer	•	•					•
MER	•	•	•	•			
GALEX	•	•	•	•			•
RHESSI	•	•	•				•
TIMED	•	•	•				•
GENESIS	•	•	•				•
Mars Odyssey	•	•	•		•		•
WMAP	•	•	•		•	•	•
WIRE	•	•	•				•
TRACE	•	•	•	•		•	•
Cassini	•	•	•				
Mars Global Surveyor	•	•	•		•		
NEAR	•	•	•				
GPM	•	•	•			•	
OCO-2	•	•	•				•
MMS	•	•	•				
OSIRIS-REx	•	•	•			•	
GOES-R	•	•	•	•		•	
CYGNSS	•	•	•			•	
InSight	•	•	•				
SMAP	•	•	•			•	•
JPSS-1	•	•	•			•	
Solar Probe	•	•	•				
Mars 2020	•	•	•	•		•	
TESS	•	•	•			•	
IXPE	•	•	•	•		•	
TDRSS K-L							

CER Development Challenges – Improving on v2.3 Performance



NOTE: Development costs do not include Payload (WBS 5) or Launch Vehicle (WBS 8); Science Team (WBS 4) costs are passed-thru

- **PCEC v2.3 performance continues to be solid**
  - Robustness of the PCEC v2.3 model is further verified by running estimates on the 10 new missions in the PCEC database that were not included as part of the model development
  - Red diamonds indicate new mission estimates, which fall within the range of the model
  - Although not shown here, JWST has the highest error which is expected given the uniqueness and complexities of this mission

Future Plans

- **Refine data normalizations**
  - Focus on better representation of individual landed Mars mission elements
  - Ensure accuracy of all CER input candidates
- **Develop Figures-of-Merit input candidates**
  - Initial focus will be on completing the Payload Accommodations Database and developing a Payload Accommodations Complexity FoM
- **Update CERs with expanded mission set**
  - Includes 10 new missions with expanded set of CER input candidates
  - Normalized data includes 59 missions and 70 separate flight systems
- **Validate new CERs including performance comparisons to v2.3**
- **Explore cloud based solutions such as AWS to generate PCEC CERs and provide a more interactive user interface to the model**