Mission Operations Cost Estimation Tool (MOCET) 2024 Status

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2024 ICEAA Workshop
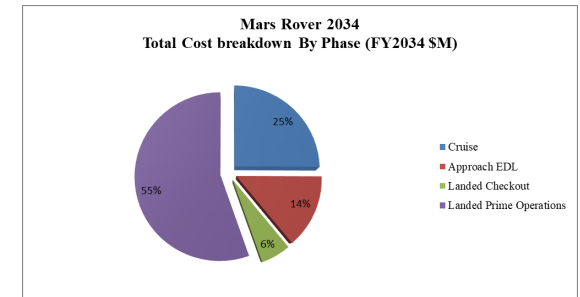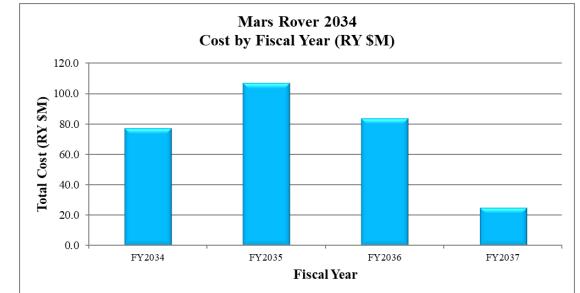*14 May 2024*

Topics
MOCET 2024 Status

- MOCET Overview

- Recent Tool Updates

- Extended Mission Modeling Overview

- The Future of MOCET & Broader Applications – Interactive Discussion

- Conclusion

MOCET Overview

- The **Mission Operations Cost Estimation Tool (MOCET)**
  - A capability for Phase E estimation jointly developed by The Aerospace Corporation and NASA Science Office for Mission Assessments (SOMA)
  - Based on **actual costs of historical missions** with emphasis on competed missions
  - Constructed by **breaking cost into the various operational phases**
  - Has **few subjective inputs**
  - Estimates total Phase E mission cost
  - Implemented entirely in Excel and requires no additional software or tools
  - Also includes a user manual which provides additional instruction and background

Mars Rover 2034
Cost by Fiscal Year (RY $M)

Mars Rover 2034
Total Cost breakdown By Phase (FY2034 $M)

Available to the public:
https://software.nasa.gov/software/LAR-18894-1

NASA internal on the ONCE Model Portal
https://oncedata.hq.nasa.gov

Help desk support:
Email: MOCET@aero.org

NASA Mission Operations Cost Estimation Tool

About MOCET...

		Legend:		
Mission Type	Planetary		Input	Apply
Mission Name	Mars Rover 2034		Calculated/Read-Only	
Mission Class	Large (New Frontiers, Directed Survey)	Inflate Costs To: FY2034	Invalid/Incomplete	
Science Theme			N/A	
Estimate Milestone	CSR			

Description	Phase Start	Duration (months)	Estimating Phase	Parameter 1	Value 1	Parameter 2	Value 2	Cost/Mo (FY34 $M)	Total Cost (FY34 $M)	Total Cost (RY $M)	Notes
Cruise	03-16-2034	6.0	Mars EDL Cruise	Rover/Lander Mass (kg)	580			11.79	71.33	71.33	
Approach EDL	09-16-2034	3.0	Approach/EDL	Cruise Avg Cost	Cruise			13.33	39.87	40.30	
Landed Checkout	12-16-2034	1.0	Landed Checkout	Cruise Avg Cost	Cruise			15.39	15.68	16.09	
Landed Prime Operations	01-16-2035	24.0	Prime Landed Ops	Rover/Lander Mass (kg)	580			6.56	157.56	165.86	
End of Mission	01-16-2037										
								Total	$ 284.44	$ 293.58	
								Reserves	$ 30.91	$ 43.51	
								Total + Reserves	$ 315.36	$ 337.09	

MOCET Overview

Mission Data:

- 73 scientific robotic missions included
  - *Operational (Phase E) monthly cost broken into various operational phases*
- 5 primary mission types
  - *Planetary*
  - *Earth Science*
  - *Explorers*
  - *Other Heliophysics & Astrophysics*
  - *ISS Hosted*
- 3 primary data sources
  - *NASA SAP Business Warehouse*
  - *Monthly Status Review (MSR) documents*
  - *NASA Cost Analysis Data Requirements (CADRe)*

Tool Software:

- Programmed in Visual Basic for Applications (VBA)
  - *3000+ lines of VBA code*
  - *Scalable, fast, and robust*
  - *Enforces logic constraints to mitigate erroneous use*
  - *Flexible framework to model unique missions*
- Excel used as the environment & interface
  - *Does not require user to have additional software*
  - *Approachable for users of all skill levels*
- Data driven architecture for standard data
  - *Enables simple maintenance and expansion*
- User manual provided

Cost Estimating Relationships:

- 16 primary Cost Estimating Relationships (CERs)
  - *One for each unique operational phase*
  - *Fitted to monthly average rates from historical data*
- Focused on well defined non-subjective inputs
  - *Mission class, activity performed, mass*
- Developed with robust statistical processes
  - *Graphical analysis*
  - *Goodness of fit statistics*
  - *Analysis of residuals*
  - *Significance testing*
  - *Measures of performance*
  - *Cross validation*

User Community:

- Adopted as the NASA standard for Phase E estimation
  - *Used in Announcement of Opportunity (AO) competitions*
  - *Used in other independent cost assessments*
- 367 unique users
  - *223 on software.nasa.gov*
  - *144 on ONCE Model Portal*
- Public user base from around the world
  - *25 states within the US*
  - *21 countries outside the US*
- Academic applications also found
  - *108 users identified as 'Academic' or 'Representing Self'*
  - *Requested for use in class projects & cited in theses*
- Help desk maintained for user queries
  - *mocet@aero.org*

Recent Tool Updates & Plans
MOCET 2024 Status

- MOCET model continues to be updated on an annual basis
  - MOCET v1.4 was released in April of 2023 on ONCE and software.nasa.gov
  - Work on v1.5 has continued through FY23 and FY24
    - Updated CERs are complete and being programmed into the MOCET tool for an imminent release

- Changes and enhancements in v1.5
  - Additional new mission data accumulated
    - IXPE, JWST, EMIT, DART, and Lucy
  - Split out Flagships from Other Helio/Astro missions
    - JWST necessitated creating separate CER
  - Inclusion of extended mission CER suite
    - Extended mission CER development published in IEEE 2024

- Continuing research & future work
  - Level 2 WBS accumulated some additional mission data with full detail
    - Continuing to assess the best way to implement a Level 2 model
  - Exploring alternative approaches for the next generation model
    - Addressing critiques of the current model & striving to improve operations cost estimation

MOCET Mission Types Database Overview

| Mission/CER Type	Program	Missions
Earth Science	Earth System Science Pathfinder (ESSP)	CloudSat, OCO-2, CYGNSS, GRACE, CALIPSO, Aquarius
	Earth Systematic Missions (ESM)	Aqua, Aura, Terra, Jason-1, ICESat, GPM, SMAP, SORCE, Jason-2/OSTM, GRACE FO, ICESat-2, Sentinel-6
Planetary	Discovery	MESSENGER, Stardust, Deep Impact, GRAIL, Dawn, **Lucy**
	Mars Scout	Phoenix
	Robotic Lunar Exploration	LRO, LADEE
	New Frontiers	New Horizons, Juno, OSIRIS-REx
	Mars Exploration	MRO, Odyssey, MER, MSL, MAVEN, Insight, Mars 2020
	Outer Planets and Ocean Worlds	Cassini
	Living With a Star (LWS)	PSP
	Planetary Defense	**DART**
Explorers	Small Explorers (SMEX)	NuSTAR, IRIS, IBEX, AIM, GALEX, RHESSI, **IXPE**
	Medium Explorers (MIDEX)	THEMIS, Swift, WISE, TESS
	Explorer Missions of Opportunity (MO)	Suzaku (ASTRO-E2), TWINS, CINDI, GOLD
Near Earth Discovery Helio-Astro	Discovery	Genesis, Kepler
	Solar Terrestrial Probes (STP)	STEREO, TIMED, MMS
	Living With a Star (LWS)	RBSP, SDO
	Cosmic Origins	Spitzer, **JWST**
	Physics of the Cosmos	Fermi, Chandra
ISS Hosted	Earth System Science Pathfinder (ESSP)	ECOSTRESS, OCO-3, GEDI, **EMIT**
	Earth Systematic Missions (ESM)	TSIS-1, SAGE-III
	Explorer Missions of Opportunity (MO)	NICER

Bold Blue = New Mission Data in v1.5

Lucy
Credit: NASA/GSFC

Double Asteroid Redirection Test (DART)
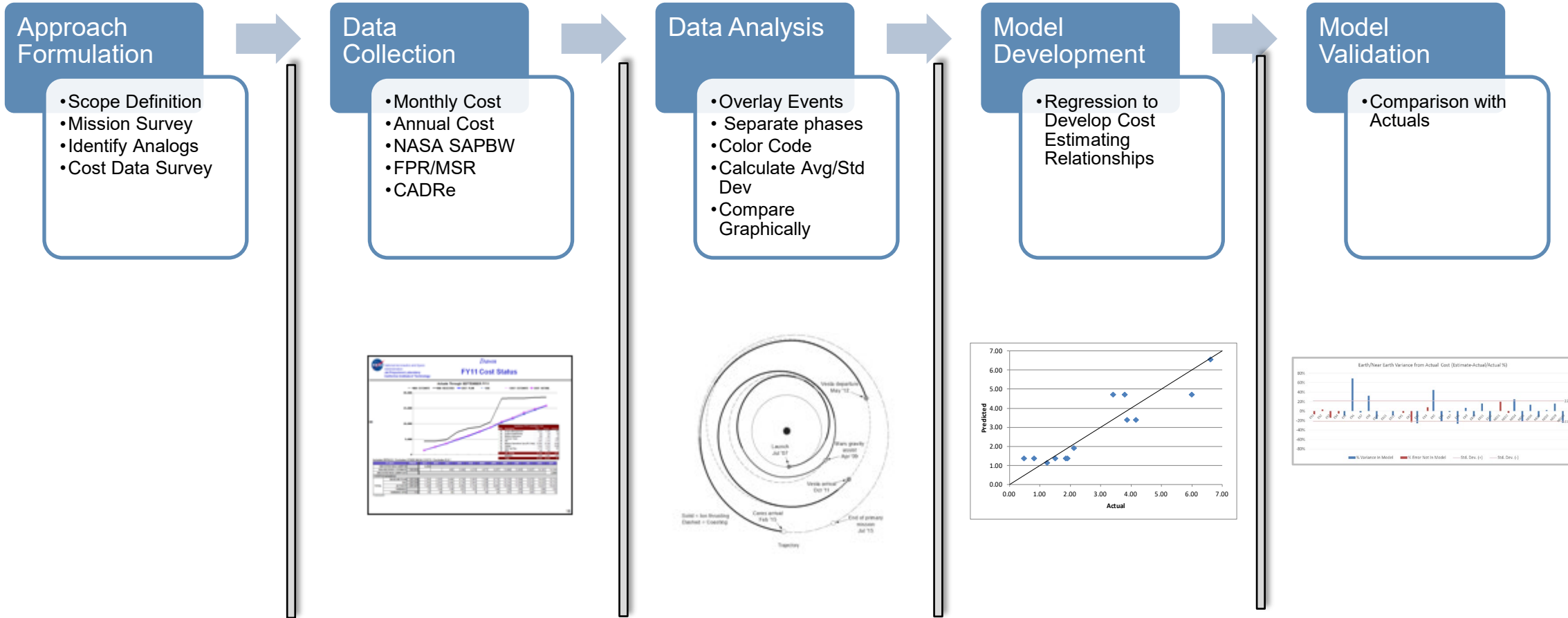Credit: NASA/Johns Hopkins APL/Joshua Diaz
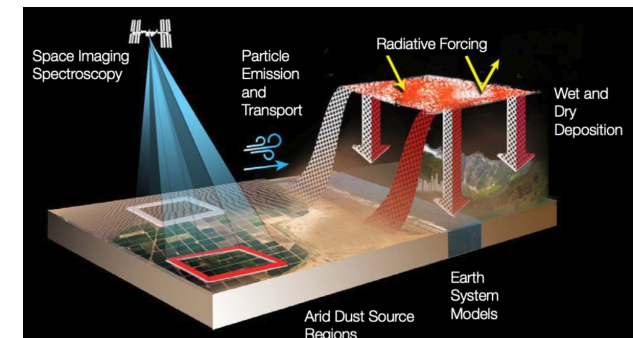
Earth surface Mineral dust source InvesTigation (EMIT)
Credit: NASA/JPL

MOCET Development Approach Overview

MOCET 2024 Status

Approach Formulation
- Scope Definition
- Mission Survey
- Identify Analogs
- Cost Data Survey

Data Collection
- Monthly Cost
- Annual Cost
- NASA SAPBW
- FPR/MSR
- CADRe

Data Analysis
- Overlay Events
- Separate phases
- Color Code
- Calculate Avg/Std Dev
- Compare Graphically

Model Development
- Regression to Develop Cost Estimating Relationships

Model Validation
- Comparison with Actuals

MOCET CERs Overview

New mission data in various CERs

CERs developed for each unique operational phase

Planetary

CER/Phase Name	New Data in v1.5	Comments/Updates in v1.5
Nominal/Quiescent Cruise CER	X	DART and Lucy data incorporated Additional OSIRIS-REx data incorporated
Checkout Cruise CER	X	DART and Lucy data incorporated
Mars EDL Cruise CER		
Orbital Operations CER	X	Additional Parker Solar Probe data incorporated
Flyby/Encounter CER	X	DART data incorporated
Approach/Orbit Insertion/Reduction CER		
Approach EDL CER		
Landed Checkout CER		
Landed Prime Operations	X	Additional Mars 2020 data incorporated
Data/Sample Analysis & Archiving	X	DART data incorporated

Earth/Near-Earth/Other

CER/Phase Name	New Data in v1.5	Comments/Updates in v1.5
Earth/Near-Earth Orbiting Checkout CER	X	IXPE and JWST data incorporated
Earth Science Prime Operations CER		
Explorer Prime Operations CER	X	IXPE data incorporated
Near Earth Discovery Helio Astro Prime Operations CER		
Near Earth Astro Flagship Prime Phase CER	X	JWST data incorporated
ISS Hosted Instrument	X	EMIT data incorporated

There are now 16 primary CERs used in MOCET, 10 of which are updated with new data in v1.5

ISS Hosted Prime Operations Phase CER

- CER Function: $Y = 0.1116 * SM^{0.4048}$

Variable	Name	Units	Definition
Y	Cost	FY23 $M	ISS Hosted Instrument average monthly prime operations phase cost
SM	Sensor Mass	kg	CBE mass of ISS instrument sensor portions

> **ISS Instruments use common interfaces, which results in a lot of extra mass of structure and electronics etc. After removing the excess mass, a reasonable CER could be derived.**
>
> **ISS operations CER estimates using sensor mass which includes primarily optics and detectors.**

- Goodness of Fit

Measure	Value
Regression Method	GERM ZMPE
Standard Error of the Estimate	12.9%
Average Percentage Bias	0.0%
Pearson's Correlation Sqd (R^2)	0.82
Number of Observations	7
Number of Input Variables	1
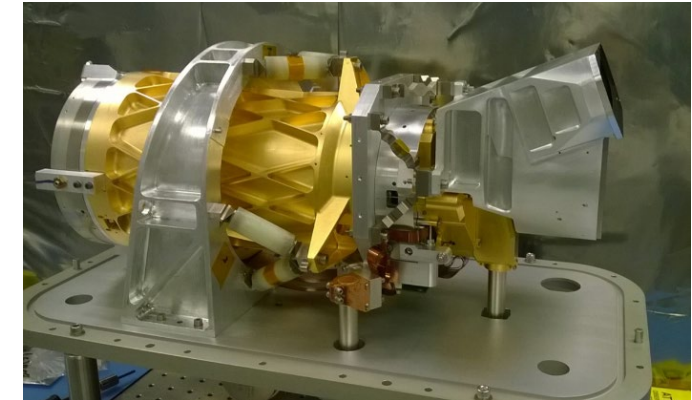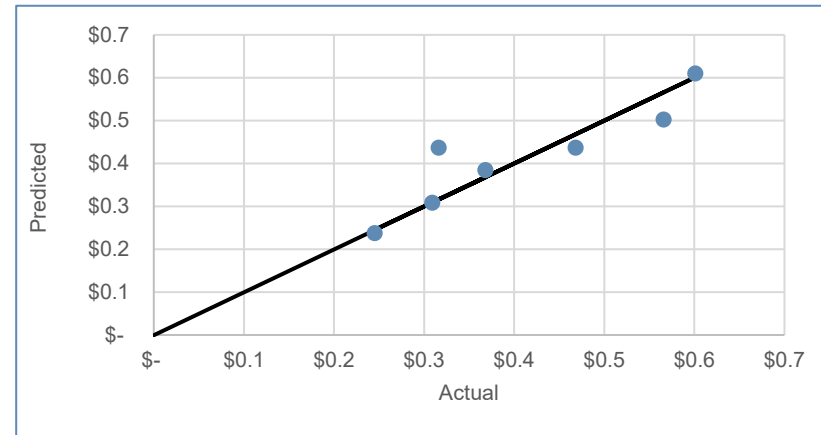
EMIT Instrument Portion
Credit: NASA/JPL

- Database

1. ECOSTRESS (SM 12.3)	4. OCO-3 (SM 66.3)	7. **EMIT (SM 41.2)**
2. TSIS-1 (SM 21.2)	5. GEDI (SM 29.1)	
3. NICER (SM 6.5)	6. SAGE-III (SM 29.1)	

Bold = New Mission

EMIT Fully Integrated
Credit: NASA/JPL

Additional Notes

- Sensor mass: include all optical components, detectors, and items labeled as sensor or telescope. Exclude all items required for ISS accommodation: pointing systems, data processing units, power supplies, and thermal systems. Exclude any large structural or thermal instrument portions. For multiple identical complex sensor instruments (multiple different optical components working together) consider only the mass of the single sensor unit. Sensor mass may include some housing and other components for smaller instruments delivered as a single integrated sensor.

Near Earth Astro Flagship Prime Phase CER

- CER Function: $Y = 7.0345 + 1.0403 * D$

| Variable	Name	Units	Definition
Y	Cost	FY23 $M	Near Earth Discovery Helio-Astro mission average monthly prime operations phase cost
D	Diameter of Aperture	meters (m) >= 0	Diameter of the aperture of a flagship optical telescope.

New Near Earth Flagship CER broken out of Other Near Earth Helio/Astro CER.

Adds another CER using a continuous variable allowing for greater range of possible costs.

MOCET CERs are only based on actual cost, so some CERs are very limited (Near Earth Flagship, Mars Landed CERs)

- Goodness of Fit

Measure	Value
Regression Method	OLS
Standard Error of the Estimate	0.02
Average Percentage Bias	0.0%
Coefficient of Determination (R^2)	0.99
Adjusted R^2	0.99
Pearson's Correlation Sqd (r^2)	0.99
Number of Observations	3
Number of Input Variables	1
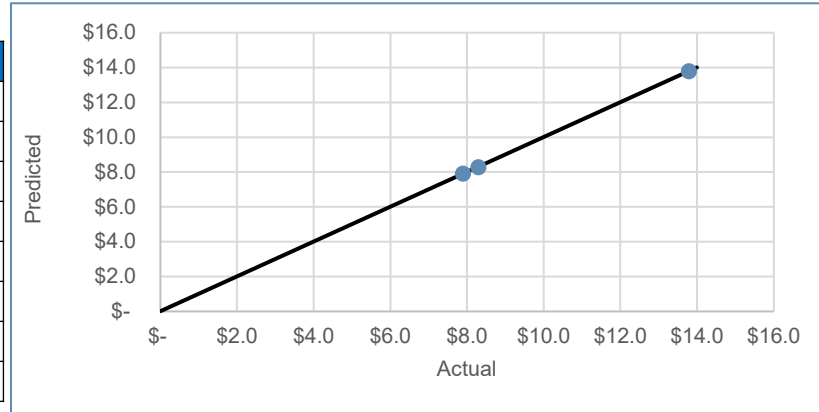
- Database

1. Spitzer (D 0.85)	3. GP-B (D 0)	
2. Chandra (D 1.2)	**4. JWST (D 6.5)**	

Bold = New Mission

JWST primary mirror

Hubble primary mirror
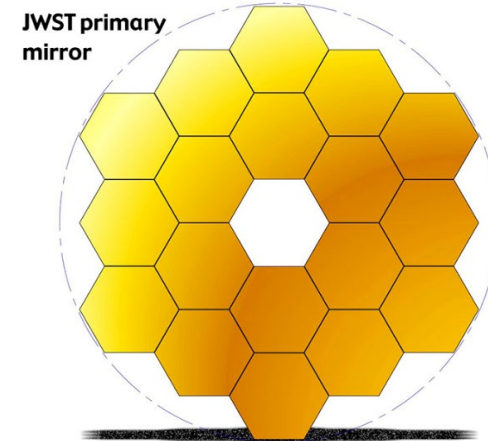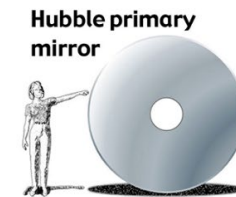
Hubble-Webb Mirror Comparison
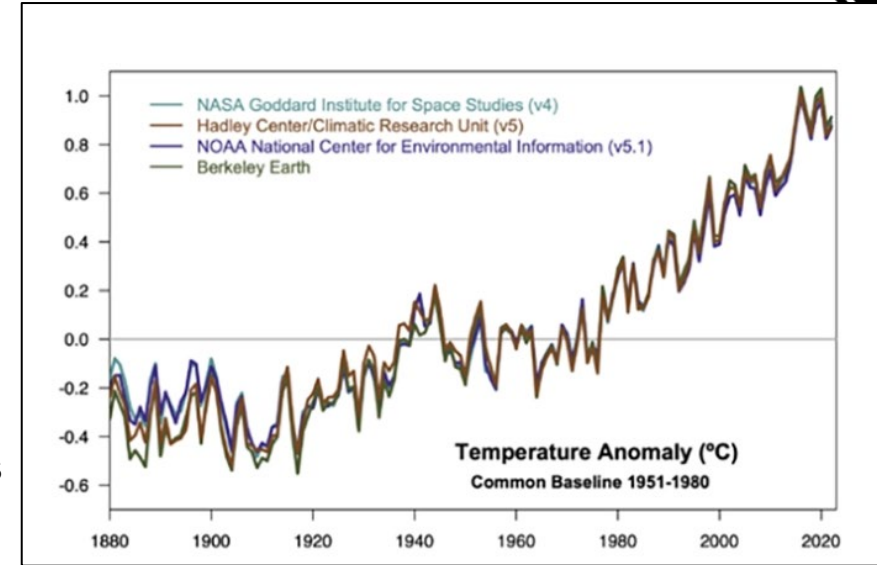**Credit: NASA/STScI**

Additional Notes

- Although GP-B was assumed to be a flagship mission, the actual Phase BCD development cost was not available. GP-B also operated quite differently than the other multi-instrumented flagship astrophysics missions, as it used sensitive gyroscopes and a guide telescope. For these reasons it has been removed.

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Extended Mission Cost Modeling
MOCET 2024 Status

- Extended Missions (EMs) are an integral part of NASA scientific research, providing continuity of data over years to decades
  - Data continuity has enabled the study of long-term phenomena
    - Climate change and other environmental trends for earth observing missions
    - Scientific discoveries such as determining the rate of the expanding universe for astrophysics missions

- EMs also capitalize on the financial investment made by NASA, providing years of additional science data for only a portion of the original cost to develop and perform the primary mission
  - Some missions have even been repurposed for new science
    - Stardust, Deep Impact, and THEMIS/ARTEMIS

- A thorough investigation of trends in NASA EM cost data has been conducted
  - Monthly cost of NASA EMs was generally found to decrease over time likely due to mission operations becoming more efficient, mission focus changing, system capability aging, and personnel transitioning
  - A model to estimate EM costs has been developed
    - Involved extensive study and normalization of monthly mission cost, experimentation with various mission type groupings, and testing of equation forms

Credit: NASA's Goddard Institute for Space Studies
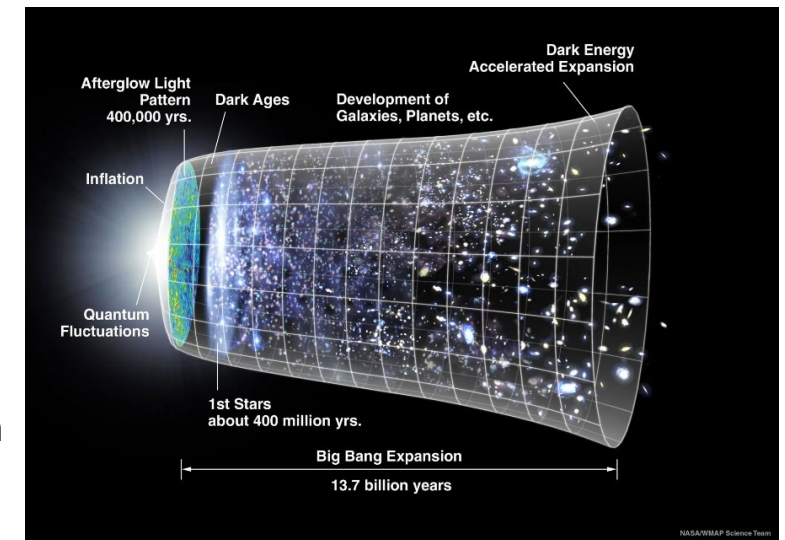
Credit: NASA/WMAP Science Team

Extended Mission Database

MOCET 2024 Status

- All data obtained from the NASA Systems, Applications & Products (SAP) Business Warehouse

- Includes 46 Missions

- 4 mission categories
  - Explorers
  - Earth Science
  - Other Helio & Astro
  - Planetary

- Further categorized by science theme and mission class

| Mission Category	Science Theme/Type	MOCET Mission Class	Mission	Launch	Prime End	End of Science Mission	Months of EM
Explorers	Heliophysics	Micro	CINDI	4/16/2008	4/16/2010	Nov 2015	69
			TWINS	3/13/2008	5/20/2010	Sept 2021	136
		Small	RHESSI	2/5/2002	2/5/2004	Jul 2018	172
			AIM	4/25/2007	6/1/2009	Mar 2023	151
			IBEX	10/19/2008	10/19/2010	Ongoing	136
		Medium	THEMIS	2/17/2007	9/30/2009	Ongoing	155
			IRIS	6/27/2013	7/26/2015	Ongoing	79
	Astrophysics	Micro	Suzaku	7/10/2005	9/30/2010	Mar 2015	54
		Small	GALEX	4/28/2003	8/25/2005	Sep 2011	73
			NuSTAR	6/13/2012	6/13/2014	Ongoing	90
		Medium	FUSE	6/24/1999	6/24/2002	Oct 2007	49
			Swift	11/20/2004	1/21/2007	Ongoing	181
Earth Science	Earth Science	Micro	AcrimSat	12/21/1999	4/1/2005	Jul 2014	104
		Small	Jason-1	12/7/2001	12/7/2004	May 2013	91
			GRACE	3/17/2002	3/1/2007	Sep 2017	144
			SORCE	1/25/2003	1/1/2008	Feb 2020	146
			Jason-2/OSTM	6/20/2008	6/30/2011	Oct 2019	99
			CYGNSS	12/15/2016	4/1/2019	Ongoing	35
		Medium	ICESat	1/13/2003	4/12/2006	Feb 2010	46
			CloudSat	4/28/2006	3/10/2008	Ongoing	167
			CALIPSO	4/28/2006	4/28/2009	Aug 2023	154
		Large	GPM	2/28/2014	5/29/2017	Ongoing	57
		Flagship	Terra	12/18/1999	3/18/2005	Ongoing	153
			Aqua	5/4/2002	6/1/2008	Ongoing	161
			Aura	7/15/2004	9/30/2010	Ongoing	137
Other Heliophysics and Astrophysics	Heliophysics	Medium	TIMED	12/7/2001	12/7/2003	Ongoing	210
		Large	STEREO	10/26/2006	10/25/2008	Ongoing	151
			SDO	2/11/2010	2/11/2015	Ongoing	83
			VAP (RBSP)	8/30/2012	11/30/2014	Oct 2019	59
			MMS	3/12/2015	9/1/2017	Ongoing	53
	Astrophysics	Large	Fermi	6/11/2008	8/28/2013	Ongoing	102
			Kepler	3/7/2009	11/12/2012	Oct 2018	72
		Flagship	Hubble	4/24/1990	5/1/2005	Ongoing	219
			Chandra	7/23/1999	4/1/2005	Ongoing	221
			Spitzer	8/25/2003	5/25/2006	Jan 2020	164
Planetary	Orbital	Medium	MGS	11/17/1996	1/31/2001	Nov 2006	38
			Mars Odyssey	4/7/2001	8/24/2004	Ongoing	185
			MESSENGER	8/3/2004	3/17/2012	Mar 2015	36
			Dawn	9/27/2007	6/30/2016	Oct 2018	27
			MAVEN	11/18/2013	11/14/2015	Ongoing	75
		Large	MRO	8/12/2005	10/1/2008	Ongoing	135
			LRO	6/18/2009	10/1/2012	Ongoing	114
		Flagship	Cassini	10/15/1997	7/1/2008	Sep 2017	110
	Landed	Medium	InSight	5/5/2018	13/31/2020	Dec 2022	14
		Large	MER A	6/10/2003	4/26/2004	Jul 2017	159
			MER B	7/7/2003	4/26/2004	Dec 2022	14
		Flagship	MSL	11/26/2011	9/29/2014	Ongoing	91

Extended Mission Data Investigation

MOCET 2024 Status

- Prime Average included as part of the investigation
  - Prime Average is the cumulative average of the prime mission
  - Investigation including mission's prime data alongside 12-month average extended mission data
  - 12-month moving average averages 12 months of data, starting with the last 11 months of prime mission and first month of extended mission

- Started by grouping missions in finer categories
  - Size
  - Program
  - Theme

- Developed CERs categorized by Science Theme, but went back to Mission Category

- Higher-level mission groupings perform consistently and are more flexible for adding future missions

SMEX Heliophysics Cumulative Average
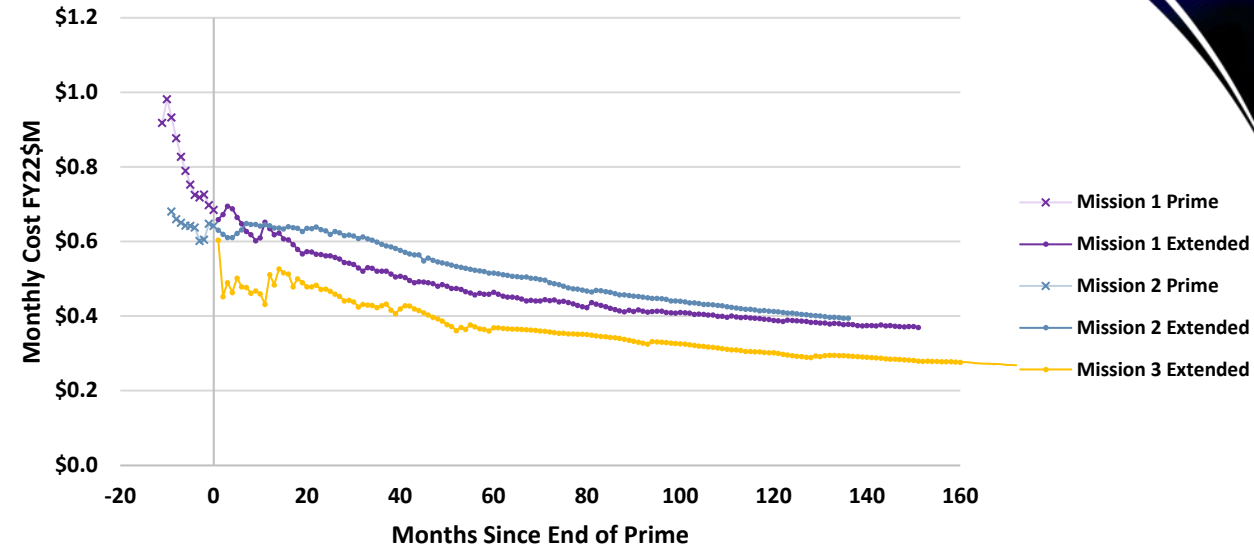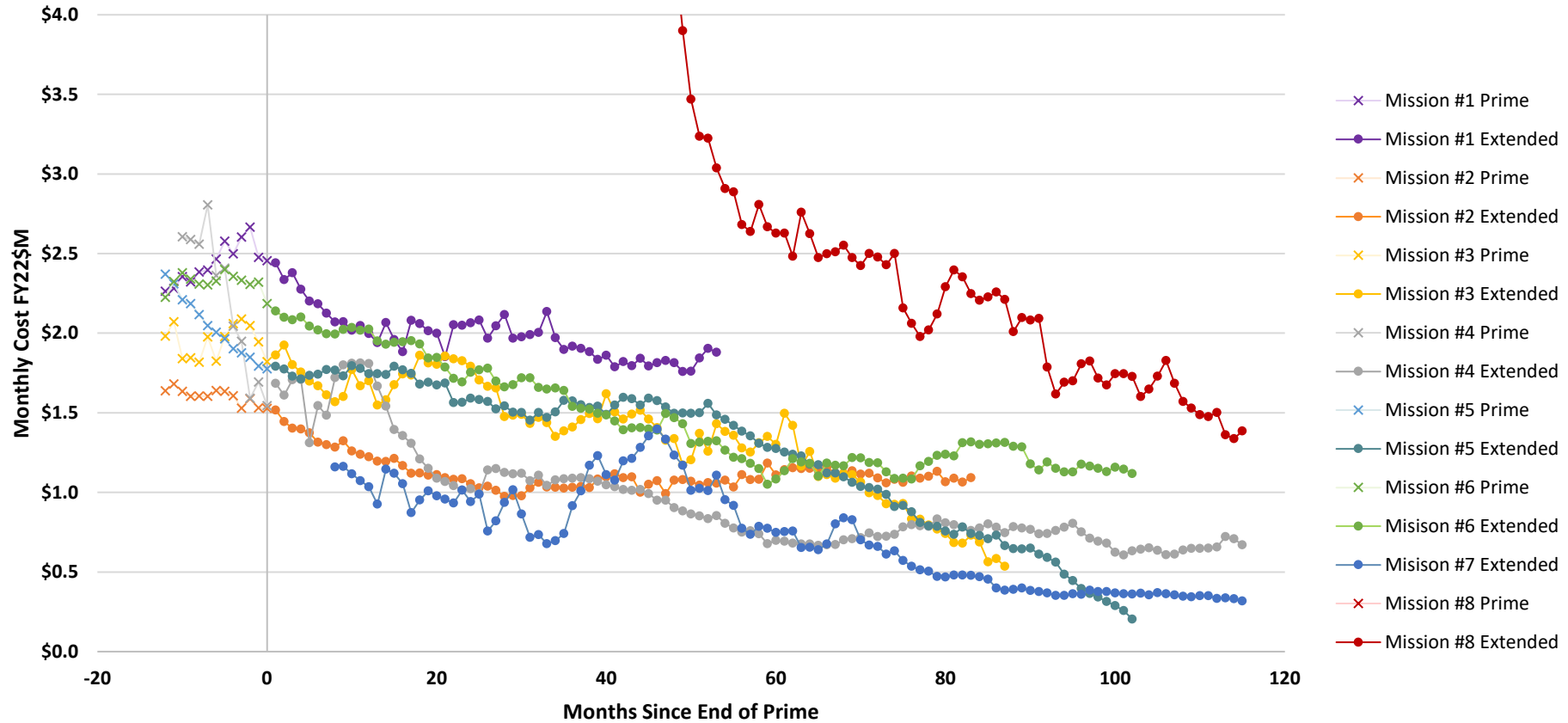
SMEX Heliophysics 12 Month Moving Average

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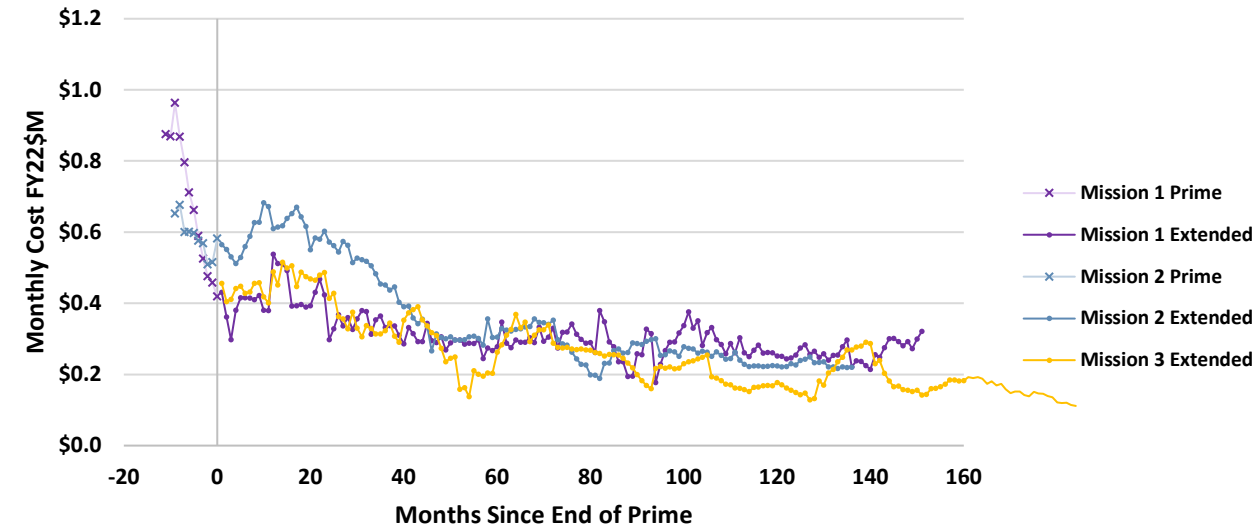
Extended Mission Data Investigation

MOCET 2024 Status

Other Heliophysics & Astrophysics 12 Month Moving Average

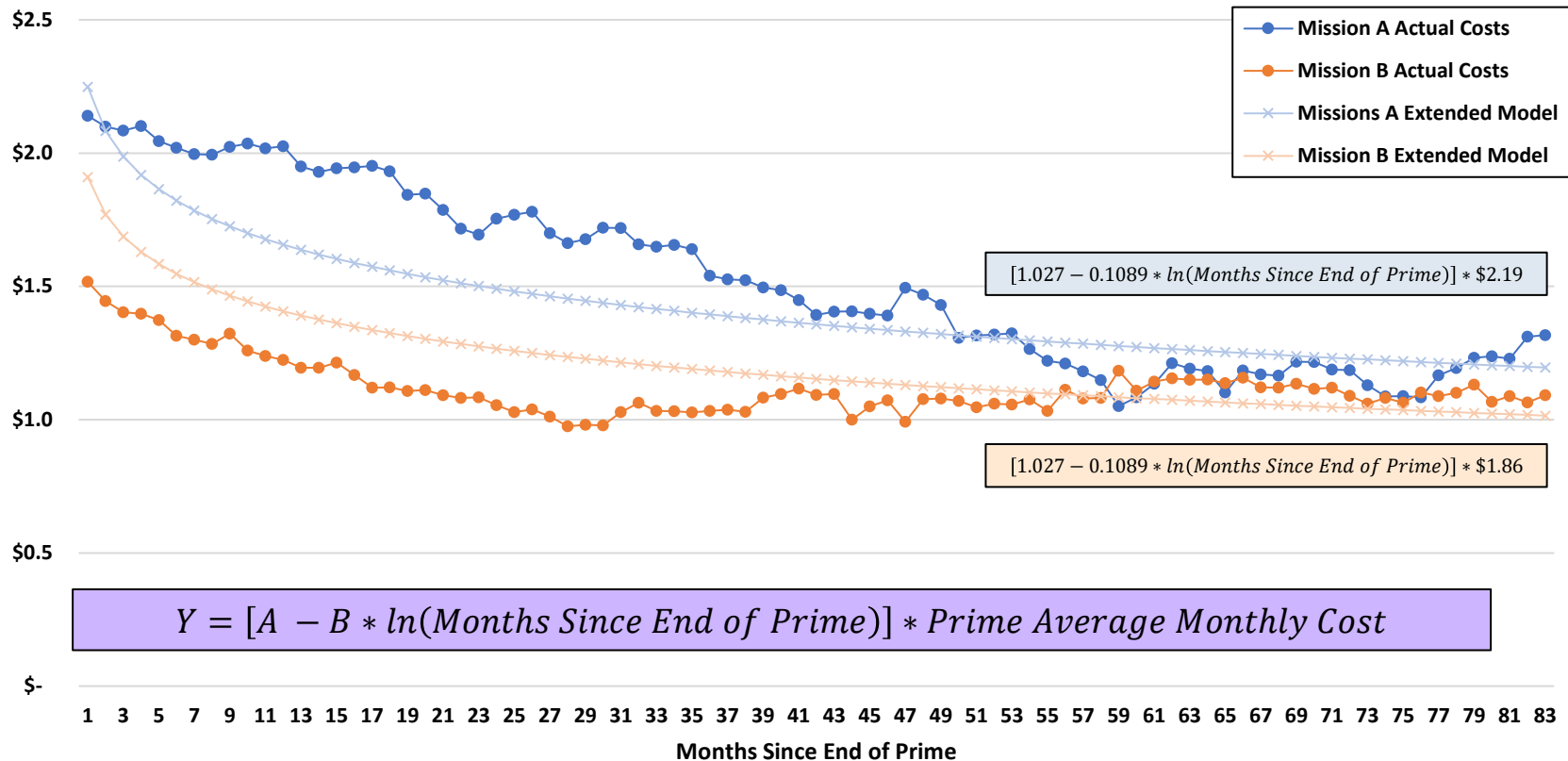Some missions and data not used due to off-nominal operational conditions

Missions shown without prime data are not used in Extended Mission modeling

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Extended Mission Equation Form

MOCET 2024 Status

- Various configurations of scaled logarithmic equations including the prime average were attempted
  - Prime average term outside the logarithmic equation was determined to have the best performance
  - First term accounts for starting cost of extended mission
  - Second term accounts for the scaling of the decrease in cost over time
    - More expensive mission decreased more rapidly, less expensive missions decreased at a slower rate

$$[1.027 - 0.1089 * ln(Months\ Since\ End\ of\ Prime)] * \$2.19$$

$$[1.027 - 0.1089 * ln(Months\ Since\ End\ of\ Prime)] * \$1.86$$

$$Y = [A - B * ln(Months\ Since\ End\ of\ Prime)] * Prime\ Average\ Monthly\ Cost$$

Months Since End of Prime

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Extended Mission Cost Model Final CERs

MOCET 2024 Status

CER Group	Missions	Equation	No. Data Points	No. Missions	r2	SEE (%)
Explorers	AIM, IBEX, RHESSI, THEMIS, IRIS, Swift, NuSTAR, GALEX, Suzaku, TWINS, CINDI	$Y = [1.3765 - 0.192 * ln(m)] * p$	1297	11	0.69	0.35
Earth Science	SORCE, GRACE, CYGNSS, OSTM, Jason-1, AcrimSat, CloudSat, CALIPSO, ICESat, Aqua, Aura, Terra*, GPM	$Y = [1.0225 - 0.0625 * ln(m)] * p$	1528	13	0.91	0.29
Other Helio/Astro	Kepler, Fermi, MMS, SDO, VAP, STEREO, TIMED	$Y = [1.6355 - 0.2714 * ln(m)] * p$	731	7	0.76	0.25
Planetary – Orbital Ops	MRO, MESSENGER, MAVEN, Mars Odyssey, Dawn, Cassini, LRO	$Y = [1.3001 - 0.1572 * ln(m)] * p$	632	7	0.97	0.13
Planetary - Landed	MSL, MER, InSight	$Y = [1.4207 - 0.2551 * ln(m)] * p$	256	3	0.54	0.38

m = months since end of prime mission, p = prime monthly average cost

- Of the 46 missions studied, 41 were used in the CERs

- Final candidate CER equations selected produce the most consistent results across all tested groupings and mirror the MOCET mission groupings

- Consistency between the EM cost model and MOCET allows the models to be used in combination

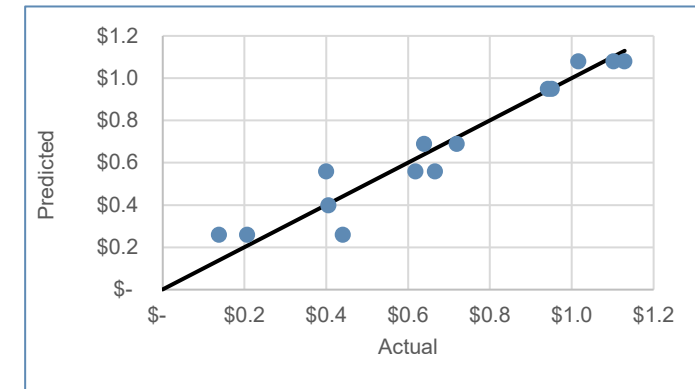- Full methodology and details published in IEEE 2024 publication

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The Future of MOCET
Interactive Discussion

- MOCET was first released to the NASA science community in 2015
  - Available data has increased since initial development… but remains limited
  - Always used a parametric approach, but greatly improved after first release to current $Y = 0.5458 + 0.3907 * IMe - 0.3520 * IMi + 0.1508 * IA$

- Existing Parametric Model
  - Primarily based on correlative factors rather than causal factors (e.g. mass)
  - Single equation with single output … but there is a range within the data!
  - Limitations – adjustment of other mission inputs don't affect the outcome
  - Benefits – hard to manipulate inputs; forces the conversation about claims of savings

- What about a Workload Model?
  - The actual "stuff" being done can be modeled, instead of just correlation
  - If there are more knobs to turn, a wider spread of possibilities can be modeled
  - Could it be calibrated with existing cost and staffing data?
  - Limitations – hard to know exactly what all the "stuff" in the model should be; takes longer to develop estimates
  - Benefits – makes more engineering sense; can provide more detail of what is in the cost

- Are there other (better) approaches?

Broader Applications of MOCET to the Community

Interactive Discussion

- The building block approach used by MOCET could be applicable to other programs that consist mostly of 'activity-based' labor tasks
  - Space mission operations have the advantage of their schedules being dictated largely by physics and activities are mostly serial, so the cost behavior is reasonably predictable
  - The same framework could also be parallelized for other situations with multiple simultaneous activities

- A data driven approach, even with little data to start, has multiple benefits
  - Helps to benchmark cost realism
  - Can be continuously updated with new data to expand and adapt capability

- Requires a commitment to collect the data and continuously fund the development
  - Proper data is a common challenge
    - Implementing controls to capture the data
    - Capturing the data with the needed level of fidelity (e.g., monthly data, lower level WBS)
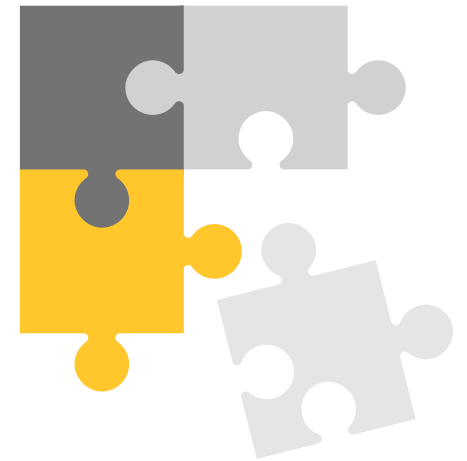
Conclusion
MOCET 2024 Status

- The 2024 status of MOCET updates and research has been presented

- MOCET will continue to be periodically updated with new mission data

- New implementation methods being considered for future release

- Model is currently being used by both evaluators and proposers

- We will continue to engage and grow the user community

James Webb Space Telescope
Credit: NASA

Selected Publications

- Extended Missions Operations Costing Capability for NASA Science Missions, 2024 IEEE Aerospace Conference, Big Sky, MT
- Mission Operations Cost Estimation Tool (MOCET) 2023 Status Update, 2023 NASA Cost and Schedule Symposium, April 2023, Pasadena CA
- Mission Operations Cost Estimation Tool (MOCET), 2017 IEEE Aerospace Conference, Big Sky, MT

MOCET Contact

Available to the public:
https://software.nasa.gov/software/LAR-18894-1

NASA internal on the ONCE Model Portal
https://oncedata.hq.nasa.gov

Help desk support:
Email: MOCET@aero.org

Questions?

Thank you