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NASA and Smallsat Cost Estimation Overview and Model Tools

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Jet Propulsion Laboratory
California Institute of Technology

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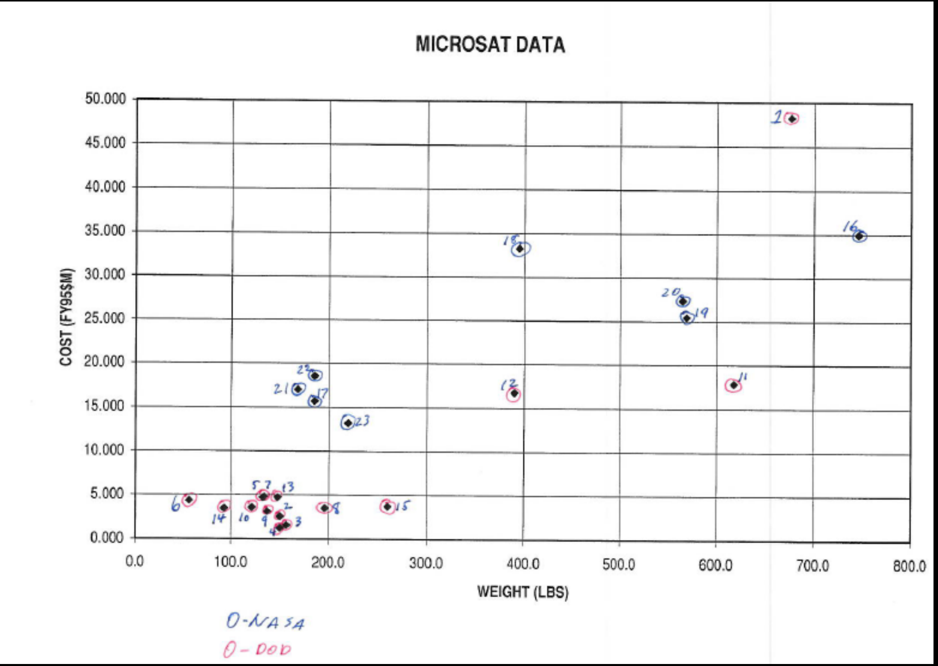
Agenda

- Introduction/Background
- Cost estimating Basics
- Cost model overview (applicable for small missions)
- Generating a Small Sat Cost Estimate Example
- Introduction to Cubesats/Microsats and NASA COMPACT
- Recommendations
- Questions

Introduction/Background

NASA smallsats and microsats cost estimating

- Small sat cost estimating record dated about ~25 years
  - Mix of NASA and DOD mission
- Small Sat Satellite technology very different from today
  - Not a lot of commercial vendor
  - Limited launch rides
  - Spacecraft unstable due to limited technology and hardware
  - Battery powered
- Utilization for smallsats/cubesats increased in mid to end of 2000s



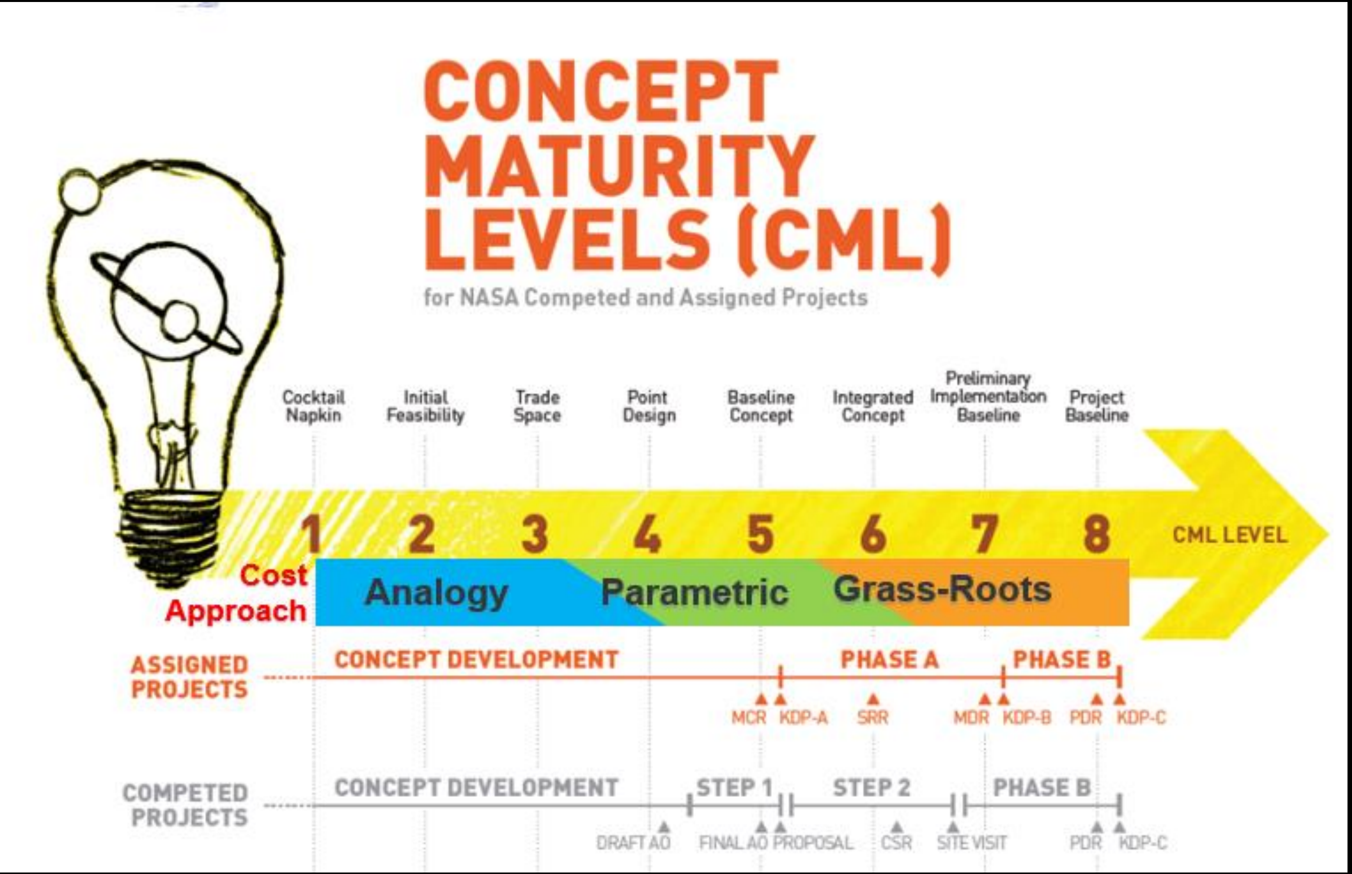
NASA and DoD Microsat Cost/Mass Data (1995)

Definition of Small Sat* for duration of this talk

- Small mission references to any mission <~$250M (such as MIDEX, SMEX, EVM, etc…)
- Small Sat <150kg to 1,500kg
  - Examples – WISE, SWIFT, etc…
- Microsats ~30kg to <150kg
  - Examples – Cygnss
- Cubesats 1U to to ~27U (~35kg)
  - Examples – MarCO, Asteria, etc…

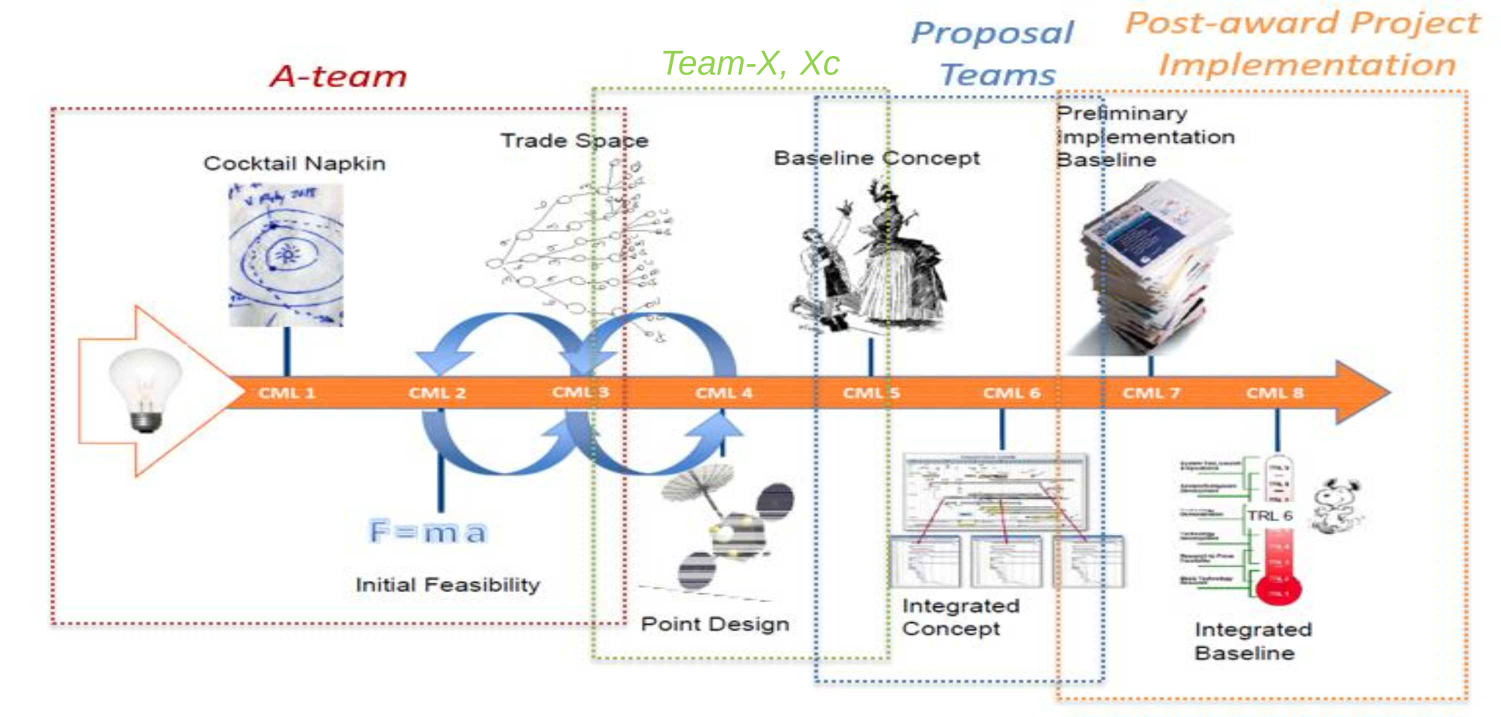
- *The definition here does not reflect NASA/JPL/Industry as everyone has a different view what small sat means to their project and organization. This reflects the author's view.

CML and Commonly Used Cost Approach



Concept Maturity Level

JPL Design/Study and Proposal Teams on the CML levels

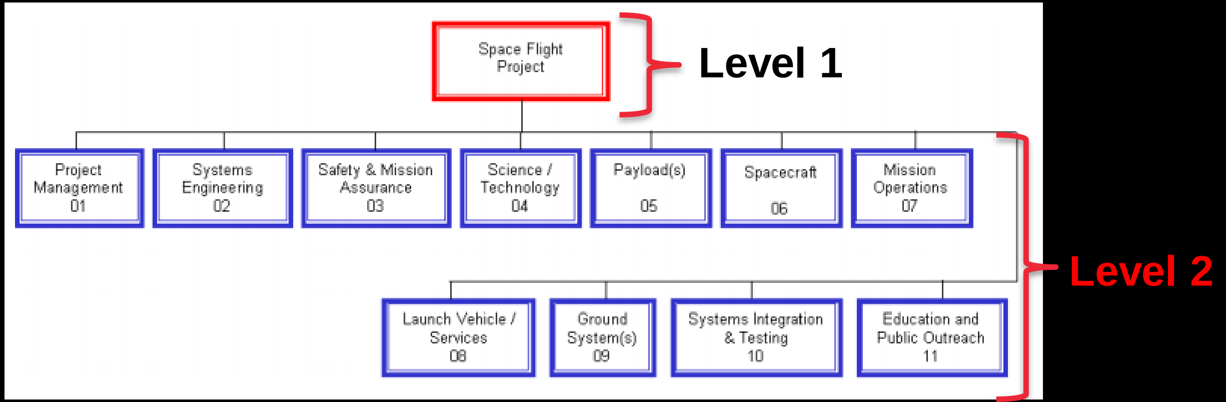


Cost Estimating Basics

NASA Work Breakdown Structure (WBS)

- Standard WBS used in NASA and (other industries/academia)

WBS	Description
1	Project management
2	Systems Engineer
3	Safety and Mission Assurance
4	Science and Technology
5	Payload Instruments
6	Spacecraft
7	Mission Operations
8	Launch Vehicle / Services
9	Ground System(s)
10	Systems Integration and Testing
11	Education and Public Outreach 1% of total (not including LV)
	Subtotal (Phase A-D)
	Costs Reserve (25%, Phase A-D and 15% Phase E)
	Total with Reserve



Cost reserve varies by mission type and organization

- Link to the Complete NASA Standard WBS
  https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20110012671.pdf

Cost Estimating Methods – 3 types

Analogy

- Data Driven
- Based on similarity / analogous
- Extrapolation and adjustments to actual
- Pros: Quick rough order magnitude (ROM) estimate with a few known characteristic
- Cons: Getting good data (normalized) might be difficult; Analogy data might not be available because of new systems uniqueness

Parametric

- Data Driven
- Statistical relationship model based on historic actuals between costs and a system or performance characteristics
- Typical parametric cost models are based on mass and power
- Pros: Provides estimate confidence based on actual data and statistical relationship
- Cons: very time consuming to go through initialize data for modeling
- Need to vet the data to make sure its good clean data (normalize)
- Questionable when modeling outside of its relevant data range

Grassroots

- Data Driven
- Also known as "bottoms-up"
- Experienced and / or knowledge from subject matter expert on proper staffing, procurements, etc…
- Pros: Defensible with detailed and credible basis of estimate (vendors quote, institutional commitment, etc…)
- Cons: Time and costly activity– very heavy on resource loading estimates and ensuring correct labor and inflation rates; not suitable for a quick ROM

Analogy based example

Small spacecraft bus

- Estimate the cost of the spacecraft by analogy method
- New Spacecraft = ~200kg will cost $?
- Based on historic SMEX missions, average spacecraft mass = ~150 kg and $50M
- $\frac{150\ kg}{\$50\ M} = \frac{200\ kg}{\$\ x\ M\ (New\ Spacecraft)}$ = $67M New Spacecraft

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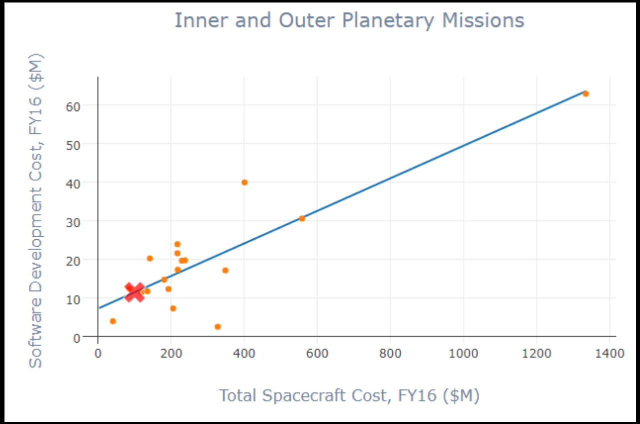
Parametric based example

- A look into the past, present, and future
- Estimate flight software cost by parametric method for inner and outer planetary mission if your spacecraft cost $100M
- Dependent variable = Total Spacecraft Development Costs, $100M
- Estimated Software Cost = $11.2M

- Example and screenshot reference to actual NASA ASCoT Tool.



Total Software Development Estimated Cost

11.46 $M ± 7.73 $M

Statistics

$\hat{Y} = 0.04 \times (\text{SC Cost}) + 7.24$

$t_{int} = 3.34$

$t_{SC\ Cost} = 6.77$

$R^2 = 0.74$

$F = 46$

$n = 17$

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Grass-Roots Cost Estimation

- Resource loading
- Typical cost categories includes:
  - Direct Labor (FTE/WYE)
  - Procurements
  - Travel
  - Services
  - Equipment
  - CM&O (Center Operations and Management – NASA centers)
- Example:
  - 3 FTE at $150k/year per FTE (institutional labor rates) = $450k (FY20$)
  - Travel (Use institution/GSA rates for per diem and meals), etc.…
  - Procurements – some organization charges

Steps to getting started with generating a cost estimate

For early CML 1-5

1. Know what type of mission you want to estimate cost for (Earth orbiting, planetary, observatory, etc…)
2. Gather the data (similar like missions, spacecraft bus, instrument type – telescope, remote sensing, etc…)
3. Some knowledge of design parameters such as mass, power, instrument aperture, s/c volume, etc…
4. Choose and know your cost models tools to estimate the hardware costs
   -WBS 5. Payload instrument (Remote sensing, in-situ)
   -WBS 6. Spacecraft (cubesat, small sat, etc…)
1. Use your data to generate wraps to the costs by WBS (PM, SE, S&MA, etc…)
   1. In some cases, some cost model will already have this set of wraps for you
2. Perform multiple cost estimations using various cost model tools and compare results
3. Consider cumulative probabilistic analysis
4. Refine and update your estimate
   1. With commercial vendor’s quote, etc…
5. Defend your estimate with a strong basis of estimate (BOE)

COST MODEL OVERVIEW

Cost Models available to NASA Community*

COST MODELS AND TYPE OF COST ESTIMATION		Spacecraft			
Cost Models	Estimation Type	Small Sats	Cubesats/ Microsats	Instruments	Full Mission Costs
NASA Instrument Cost Model (NICM)	Parametric			✓	
NASA Project Cost Estimating Capabilities (PCEC)	Parametric	✓			✓
PRICE True Planning	Parametric	✓		✓	
Small Spacecraft Cost Model (SSCM-19)	Parametric	✓			
NASA CubeSat Or Microsat Probabilistic Analogy Cost Tool (COMPACT)	Analogy/ (Parametric model coming soon)		✓		✓

*Check with NASA HQ OCFO's Strategic Investment Division (SID) james.k.johnson@nasa.gov or your Cost Estimation Division/Section. Not all tools listed might be available due to changing license agreements.

NASA Instrument Cost Modeling Tool (NICM)

- Current version is NICM 8.5
- Version 9.0 releasing soon
- Data collection of 250+ NASA and industry built instruments
- All normalized
- Capable of Class D cost estimation
- Cost and Schedule Rule of Thumb (ROT) by phase and instrument type
- Cryocooler also now added to the model

	Optical Earth Orbiting	Optical Planetary	Particles Earth Orbiting	Particles Planetary	Fields	Active Microwave	Passive Microwave
A	✓	✓	✓	✓	✓	✓	✓
B	✓	✓	✓	✓	✓	✓	✓
C	X	X	✓	✓	X	X	X
C: NICM-E	✓	X	✓	X	✓	X	X
D	X	X	X	X	X	N/A	N/A

Figure 9-1 NICM VII Service Matrix

A	✓	✓	✓	✓	✓	✓	✓
B	✓	✓	✓	✓	✓	✓	✓
C	✓	✓	✓	✓	✓	✓	✓
D	✓	✓	✓	X	X	N/A	N/A

Figure 9-2 NICM VIII Service Matrix

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NASA Project Cost Estimating Capability Tool (PCEC)

- Previous version known as NAFCOM (NASA Air Force Cost Model Capabilities)
- Current Version v2.2
- Data set based on actual NASA launched missions
- Wide range of mission types (EO, Planetary, etc… and mission size (small, medium, etc..)
- Cost output to NASA Standard WBS
- Normalized data

Download https://www.software.nasa.gov

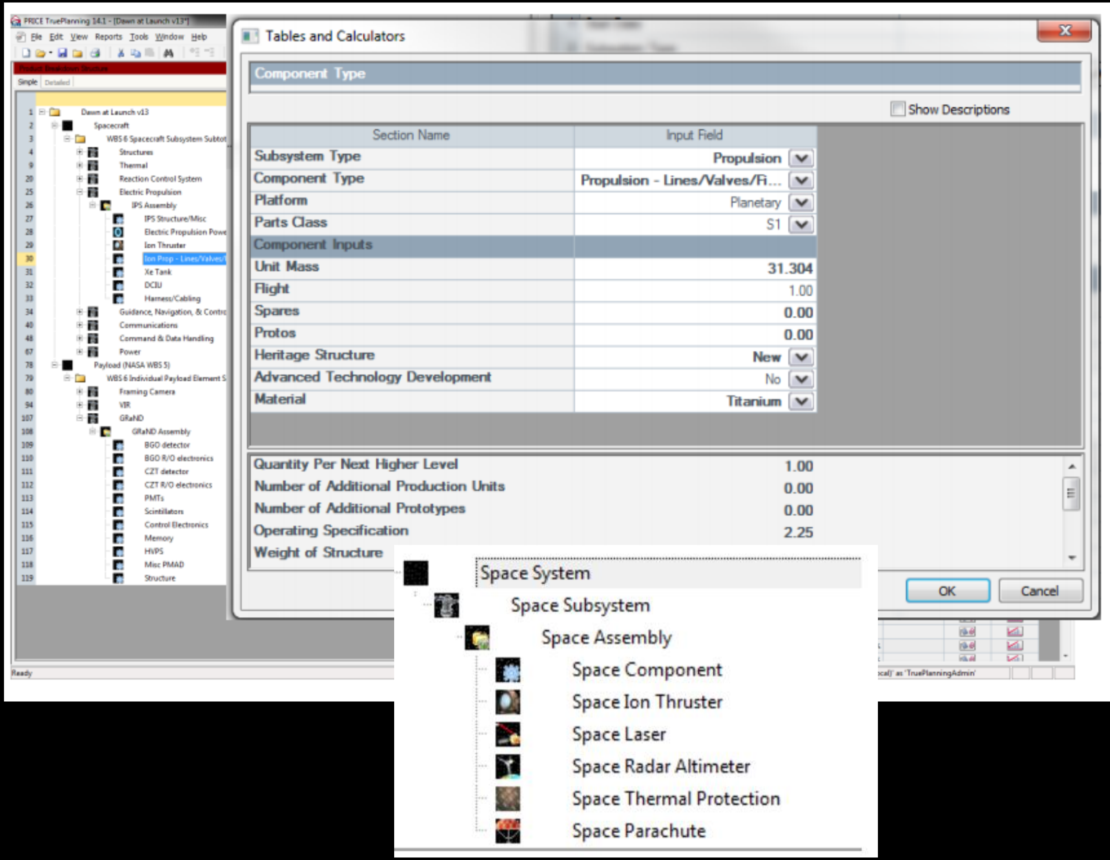
Main Support: MSFC-PCEC@mail.nasa.gov

Earth Sci	Heliophy
Astrophy	Planetary

	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

PRICE – True Planning, NASA Space Mission Catalog

- NASA Space Mission Catalog
- ~50+ NASA space mission - Astrophysics, Heliophysics, Earth Science, and Planetary Missions
- Cost estimate for system and subsystem level (CDH, Propulsion, Power, etc…)
- Heavily detailed on inputs
- Mission types Mission Class A/B, B/C, and C/D



Aerospace Small Spacecraft Cost Model (SSCM)

- Current version 2019
- Started in mid-1990's by Dr. Eric Mahr and Dave Bearden
- Data based on NASA and DoD missions
- Parametric based
- Used for up to 1,000 kg fight system mass
- Subsystem costs breakout
- Probabilistic analysis
- Budget schedule

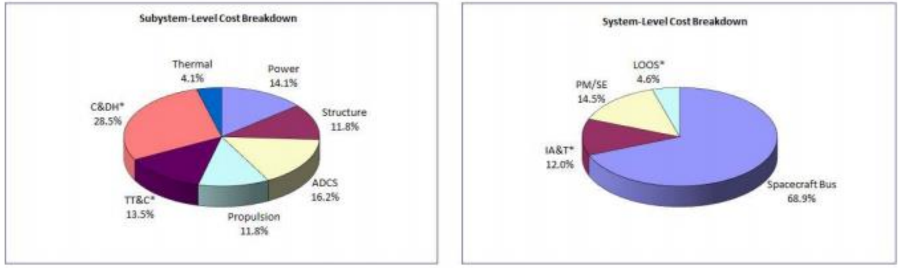


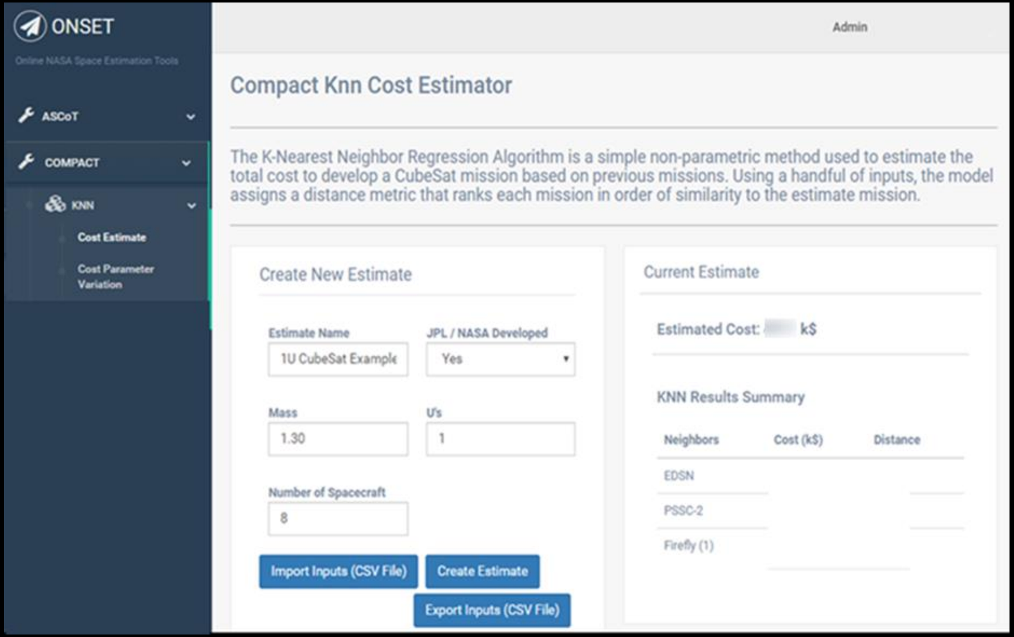
Figure 6. Cost Breakdown Plots. The chart on the right shows the subsystem-level cost breakdown. The chart on the right shows the system-level cost breakdown.

Contact: sscmrequests.mailbox@aero.org

Download Instructions: https://aerospace.org/sscm

NASA CubeSat Or Microsat Probabilistic Analogy Cost Tool (COMPACT)

- Full mission Cubesat and Microsat cost estimating tool
- Part of the NASA ONSET – Online NASA Space Estimation Tool (ONSET)
- Web-based tool
- Beta version release Summer 2020 through the NASA ONCE website:
  - https://oncedata.hq.nasa.gov
- Requires NASA credential log-ins
  - https://www.nasa.gov/offices/ocfo/functions/models_tools/CADRe_ONCE.html
- Data - NASA funded cubesat/micosat missions



Contact:

- joseph.mrozinski@jpl.nasa.gov
- michael.saing@jpl.nasa.gov

Generating a Small Sat Cost Estimate Example

Example – Astrophysics Mission

- Estimate the cost of Small Sat Ultra Violet (UV) Telescope Mission, FY2020$
- Telescope = 35 cm aperture
- Small Spacecraft
- Assumes mass below

Instrument	Mass, kg
Telescope	**100**
Spacecraft	150
Structure	39
Thermal	4
C&DH	20
Electrical Power	48
Attitude Control Subsystem	33
Communication Subsystem	7
Dry Mass	250
Wet Mass	100
Total Launch Mass	**350**

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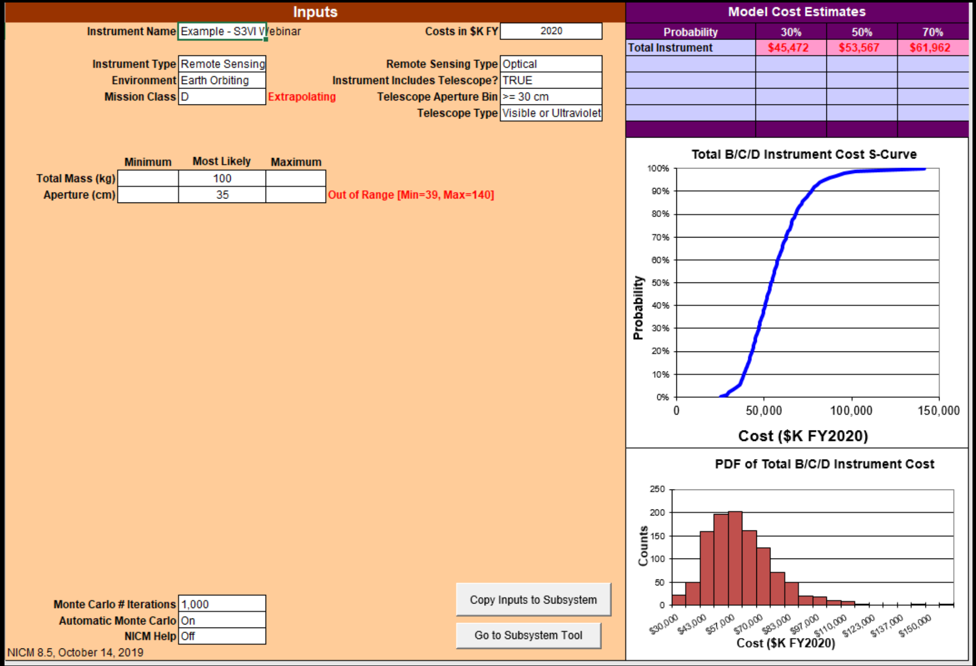
Steps to getting started with generating a cost estimate

1. Know what type of mission you want to estimate cost for (Earth orbiting, planetary, observatory. etc…)
2. Gather the data (similar like missions, spacecraft bus, instrument type – telescope, remote sensing, etc…)
3. Some knowledge of design parameters such as mass, power, instrument aperture, s/c volume, etc…
4. Choose your cost model to estimate cost (in this small sat example, we will use the following)
   1. Instrument – NICM
   2. Spacecraft – SSCM, PRICE TP (NASA Space Mission), and NASA PCEC
5. Use your data to generate wraps for WBS 1. PM, 2. SE, 3. S&MA, etc…
   1. Astrophysics Small Sat Cost ROT
6. Perform multiple cost estimations using various cost model tools and compare results
7. Consider cumulative probabilistic analysis
8. Refine and update your estimate
   1. With commercial vendor's quote, etc…
9. Defend your estimate with a strong basis of estimate (BOE)

Instrument Cost Estimation using NICM

- 50th-percentile costs = $53.6M
- Costs estimation uncertainty – “*Extrapolating*” outside the data set in the model
  - Will require you to do more homework to refine costs



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Spacecraft cost estimate using SSCM (1 of 3)

- The model only estimates development phases C and D, and according to the SSCM user guide, must add 10% for Phase B costs

SSCM
Small Satellite Cost Model

Inputs

INPUT

Technical Parameter	Units	Value	Notes
Programmatic			
Fiscal Year for Estimate	YYYY	2020	
Inflation Methodology	—	NASA	
Development Time	months	40.0	
System			
Destination	—	Earth-Orbiting	
Design Life	months	24.0	
Satellite Wet Mass	kg	350.00	
Satellite Dry Mass	kg		
Spacecraft Bus Dry Mass	kg	150.00	
Number of Instruments	#		
Power			
Solar Cell Type	—	Gallium Arsenide	
Battery Type	—		
Power Subsystem Mass	kg	48.00	
BOL Power	W	800	
Structure			
Primary Structure Material	—	Aluminum	
Structure Subsystem Mass	kg	39.00	
ADCS			
Star Tracker?	—	Yes	
ADCS Subsystem Mass	kg	33.00	
Pointing Control	deg	0.001	
Propulsion			
Monopropellant or Bipropellant?	—		
Propulsion Subsystem Dry Mass	kg		
TT&C/C&DH			
Communications Band	—		
TT&C/C&DH Subsystem Mass	kg	24.00	
Transmit Power	W	100	
Downlink Data Rate	kbps	24000	
Thermal			
Thermal Subsystem Mass	kg	4.00	

Technical Parameter	Range				
	Low	Minimum	Value	Maximum	High
Development Time					
Design Life		0.2	24.0	96.0	
Satellite Dry Mass					
Spacecraft Bus Dry Mass		52.00	150.00	598.00	
Number of Instruments					
Power Subsystem Mass		14.77	48.00	201.00	
BOL Power (Power)		150	800	2200	
BOL Power (Structure)					
BOL Power (Thermal)		81	800	10500	
Structure Subsystem Mass		6.70	39.00	298.00	
ADCS Subsystem Mass		0.60	33.00	103.80	
Pointing Control	66.7%	0.003	0.001	5.000	
Propulsion Subsystem Dry Mass		7.06		118.20	
TT&C/C&DH Subsystem Mass		4.70	24.00	115.40	
Transmit Power		1	100	100	
Downlink Data Rate		32	24000	150000	
Thermal Subsystem Mass		0.70	4.00	53.00	

AEROSPACE

SSCM
Small Satellite Cost Model

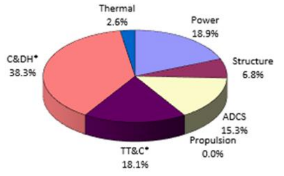
Cost Estimate

OUTPUT/RESULTS

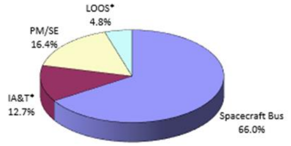
	Estimate (FY20$K)				% of	% of	
	Non-Rec	Rec	Total	Std Error	Sub-level	Sys-level	Range
Spacecraft Bus Subsystems							
Power	3,234	4,970	8,204	3,077	18.9%		
Structure	1,549	1,423	2,973	1,329	6.8%		
ADCS	3,167	3,484	6,651	2,374	15.3%		Pointing Control is 66.7% low.
Propulsion	0	0	0	0	0.0%		Select Monopropellant or Bipropellant
TT&C*	3,975	3,897	7,872	8,709	18.1%		
C&DH*	8,413	8,248	16,661		38.3%		
Thermal	587	542	1,129	493	2.6%		
Spacecraft Bus	20,925	22,565	43,489	9,642	100%	66.0%	
IA&T*	3,856	4,519	8,375	4,759		12.7%	
PM/SE	4,908	5,913	10,820	5,810		16.4%	
LOOS*	0	3,177	3,177			4.8%	
S/C Development & First Unit	29,688	36,173	65,861	12,222		100%	

*TT&C/C&DH and IA&T/LOOS costs are generated from single CERs and standard error is presented as such. Per subsystem cost presented is based on database data.

Subystem-Level Cost Breakdown



System-Level Cost Breakdown



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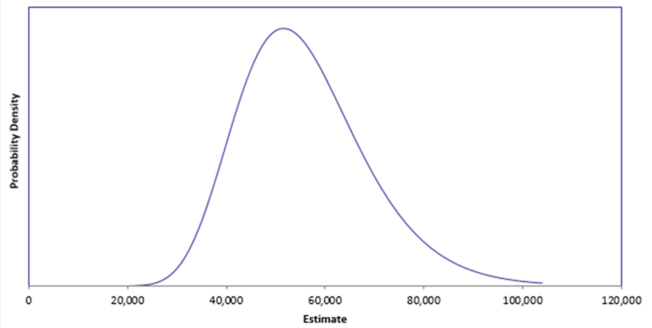
Spacecraft cost estimate using SSCM (1 of 3) (continued)

- Option to Generate Probabilistic Estimate
- Uncertainty inputs based on engineering judgement, historic data, etc…
- Select the 50th percentile estimate based on the adjusted inputs, \$54.5M then add 10% for Phase B (per SSCM guidance). = \$62.2M

SSCM Small Satellite Cost Model

Cost Risk

	Percentages		Distribution Points			Estimate (FY20\$K)	
	Low	High	Low	Most Likely	High	Mean	Std Dev
Spacecraft Bus Subsystems							
Power	60%		3,282	8,204	8,204	6,563	2,721
Structure	50%		1,486	2,973	2,973	2,477	1,161
ADCS	50%		3,326	6,651	6,651	5,543	2,128
Propulsion			0	0	0	0	0
TT&C/C&DH	20%		19,626	24,532	24,532	22,897	8,210
Thermal		30%	1,129	1,129	1,467	1,242	548
Spacecraft Bus			28,848	43,489	43,828	38,722	10,827
ATLO	75%		2,888	11,552	11,552	8,664	4,112
PM/SE	60%		4,328	10,820	10,820	8,656	4,894
S/C Development & First Unit			36,064	65,861	66,200	56,042	13,223



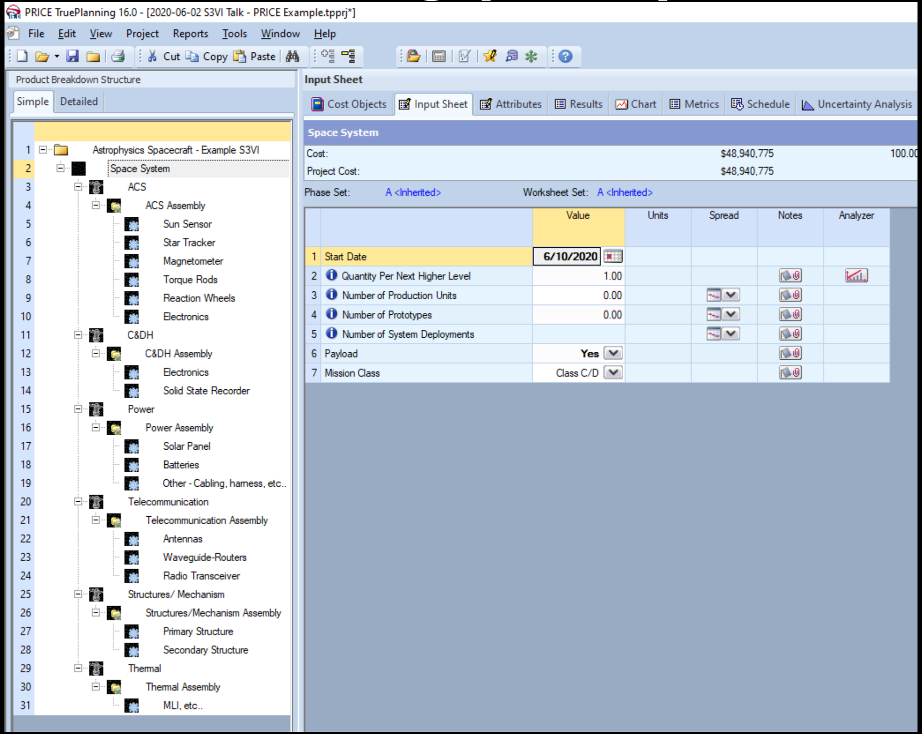
Percentiles of Cost (FY20\$K)

Percentile	Cost
10%	40,476
15%	42,852
20%	44,840
25%	46,619
30%	48,277
35%	49,865
40%	51,421
45%	52,972
50%	54,544
55%	56,163
60%	57,857
65%	59,662
70%	61,625
75%	63,816
80%	66,348
85%	69,426
90%	73,502
95%	79,988

AEROSPACE

Spacecraft cost estimating using PRICE – True Planning, NASA Space Mission Catalog (2 of 3)

- Spacecraft costs of $48.94M



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Spacecraft and full mission costs using PCEC Cost output (3 of 3)

- Total Mission costs without reserve
- Spacecraft costs of $53.6M

			Units Conversion Factor:	1.000				
FY2020 $M			Inflation Factor:	1.131				
WBS #	Level	WBS Element		Non-Recurring	Recurring Production	Non-Allocated	Operations	Total
0	1	System Name		$ 105.19	$ 49.28	$ 50.32	$ 12.42	$ 217.21
1.0	2	Project Management		$ 3.04	$ 5.21	$ -	$ -	$ 8.25
2.0	2	Systems Engineering		$ 5.16	$ 8.86	$ -	$ -	$ 14.02
3.0	2	Safety and Mission Assurance		$ 1.80	$ 3.08	$ -	$ -	$ 4.88
4.0	2	Science/Technology		$ 4.44	$ -	$ -	$ -	$ 4.44
5.0	2	Payload(s)		$ 53.64	$ -	$ -	$ -	$ 53.64
5.01	3	Payload Management		$ -	$ -	$ -	$ -	$ -
5.02	3	Payload System Engineering		$ -	$ -	$ -	$ -	$ -
5.03	3	Payload Product Assurance		$ -	$ -	$ -	$ -	$ -
5.10	3	Instruments - EMPTY ROLLUP		$ 53.64	$ -	$ -	$ -	$ 53.64
5.x	3	Payload I&T		$ -	$ -	$ -	$ -	$ -
6.0	2	Flight System \ Spacecraft		$ 32.32	$ 21.28	$ -	$ -	$ 53.60
6.01	3	Flight System Project Management		$ 1.72	$ 2.85	$ -	$ -	$ 4.56
6.02	3	Flight System Systems Engineering		$ 2.92	$ 4.84	$ -	$ -	$ 7.75
6.03	3	Flight System Product Assurance		$ 1.01	$ 1.68	$ -	$ -	$ 2.70
6.10	3	Spacecraft		$ 24.80	$ 8.80	$ -	$ -	$ 33.60
--	4	Structures & Mechanisms		$ 2.16	$ 1.49	$ -	$ -	$ 3.65
--	4	Thermal Control		$ 1.76	$ 0.34	$ -	$ -	$ 2.10
--	4	Electrical Power & Distribution		$ 4.36	$ 4.37	$ -	$ -	$ 8.73
--	4	GN&C		$ 2.58	$ 2.60	$ -	$ -	$ 5.18
--	4	Communications (SSPA)		$ 3.12	$ -	$ -	$ -	$ 3.12
--	4	C&DH		$ 10.81	$ -	$ -	$ -	$ 10.81
6.x	3	Flight System I&T		$ 1.87	$ 3.11	$ -	$ -	$ 4.99
7.0	2	Mission Operations System (MOS)		$ 1.47	$ 5.15	$ -	$ 12.42	$ 19.04
--	3	MOS/GDS Development (Phase B-D)		$ 1.47	$ 5.15	$ -	$ -	$ 6.62
--	3	Mission Ops & Data Analysis (Phase E)		$ -	$ -	$ -	$ 12.42	$ 12.42
8.0	2	Launch Vehicle/Services		$ -	$ -	$ 50.32	$ -	$ 50.32
9.0	2	Ground Data System (GDS)		$ -	$ -	$ -	$ -	$ -
10.0	2	System Integration, Assembly, Test & Check Out		$ 3.32	$ 5.70	$ -	$ -	$ 9.02
11.0	2	Education & Public Outreach		$ -	$ -	$ -	$ -	$ -

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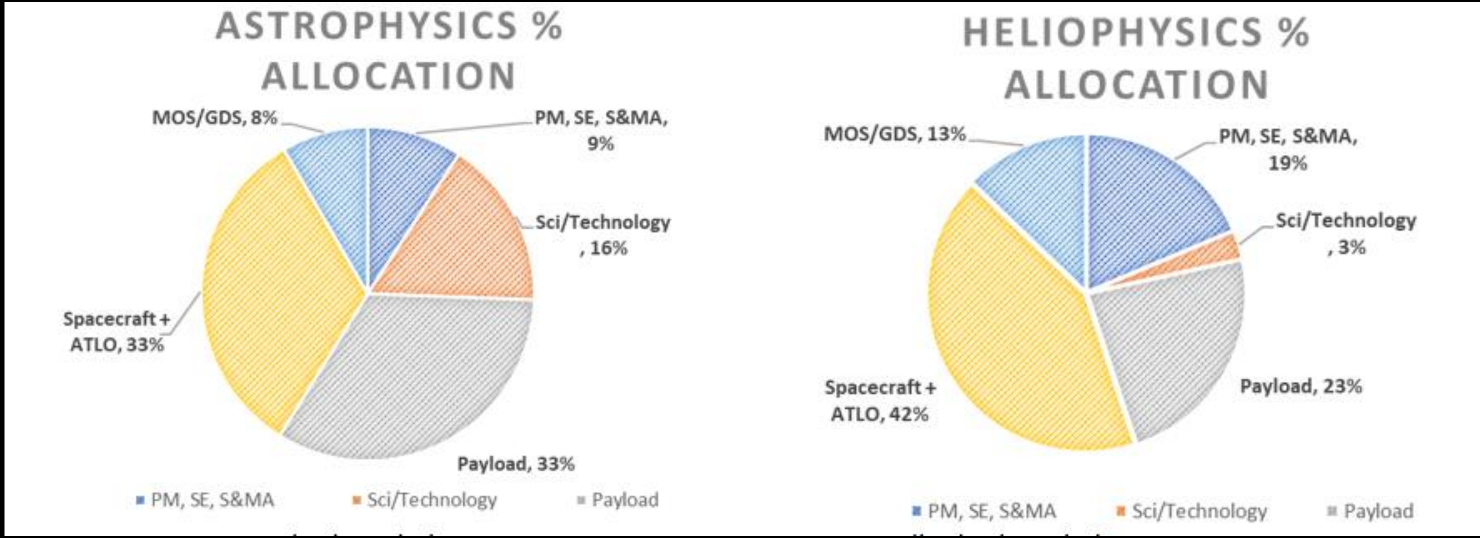
Cost Wraps – ROT†

SMEX Total Lifecycle Phase A-F* By WBS**



Astrophysics Missions:
GALEX, NuSTAR, SWAS, WIRE

Heliophysics Missions:
AIM, FAST, IBEX, IRIS, RHESSI, SAMPEX, TRACE

* Data shows that average breakout for Phase A-D and E/F cost is ~90% Formulation/Development and ~10% Operations
**Launch Ride/Services not included
† Ref to: Saing, M., Freeman, T., "NASA SMEX Mission Explorer Past, Present, and Future", Aug 14th – 16th 2018, NASA Cost and Schedule Symposium, NASA GSFC Greenbelt Maryland

Piecing it all together

Compare the results, refine it, run uncertainty analysis

WBS	Description	Total Cost, FY20$M Small Spacecraft Cost Model (SSCM)	Total Cost, FY20$M PRICE True Planning Cost Model	Approach	Total Cost, FY20$M, NASA PCEC Explorer Class, All WBS from Cost Model	Grass-Roots Estimate by Project Team, FY20$M	Average Across All Estimate
1	Project management	$ 17.2	$ 15.5	Wraps - Analogy	$ 27.0	$ 15.0	$ 18.7
2	Systems Engineer						
3	Safety and Mission Assurance						
4	Science and Technology	$ 27.5	$ 24.9		$ 4.4	$ 15.0	$ 18.0
5	Payload Instruments	$ 53.6	$ 53.6	Parametric	$ 53.6	$ 40.0	$ 50.2
6	Spacecraft	$ 60.0	$ 48.9	Parametric	$ 53.6	$ 40.0	$ 50.6
7	Mission Operations	$ 13.8	$ 12.4	Wraps - Analogy	$ 19.0	$ 15.0	$ 15.1
8	Launch Vehicle / Services	$ 50.0	$ 50.0	NASA Catalog	$ 50.0	$ 50.0	$ 50.0
9	Ground System(s)	Include In WBS 7	Included in WBS 7	Wraps - Analogy	Included in WBS 7	Included in WBS 7	Included in WBS 7
10	Systems Integration and Testing	Include in WBS 6	Included in WBS 6		$ 9.0	Included in WBS 6	$ 9.0
11	Education and Public Outreach 1% of total (not including LV)	$ 2	$ 2		$2	$ 1	$ 2
	Subtotal (Phase A-D)	$ 224	$ 207		217	$ 176	$ 206
	Costs Reserve (25%, Phase A-D and 15% Phase E)	$ 36	$ 33		$35	$ 26	$ 33
	Total with Reserve	$ 260	$ 240		252	$ 203	$ 239

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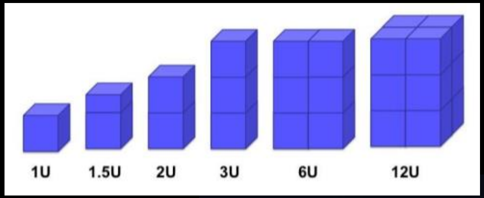
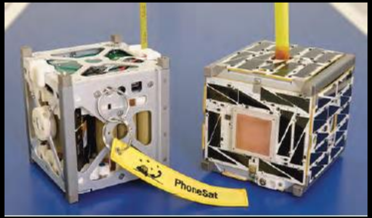
Introduction to Cubesats/Microsats and NASA COMPACT

What is a CubeSat? Microsat?

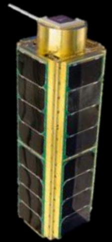
- **CubeSat = nanosatellite in a form of a cube, with each “U” measuring 10cm x 10cm x 10cm and weighs ~1.33kg (weight by ROT)**
  - The “U” cube are stackable
- **Common form factors are: 1U, 3U, 6U’s**
- **MicroSat = microsatellite with mass ranging from 10-100 kg**
- **Type and estimated mass range:**
  - Mini-satellite, 100-180 kilograms
  - Microsatellite, 10-100 kilograms
  - Nanosatellite, 1-10 kilograms
  - Picosatellite, 0.01-1 kilograms
  - Femtosatellite, 0.001-0.01 kilograms



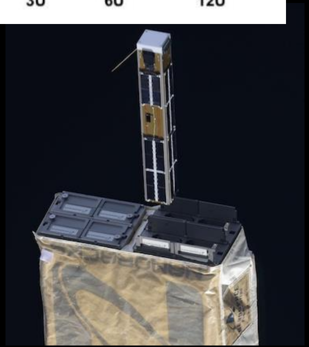
Raincube, ~6U, 12 kg each



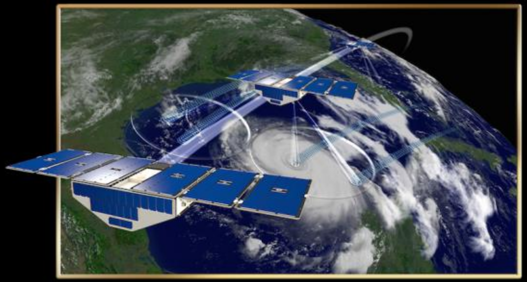
PhoneSat (1U), ~1 kg



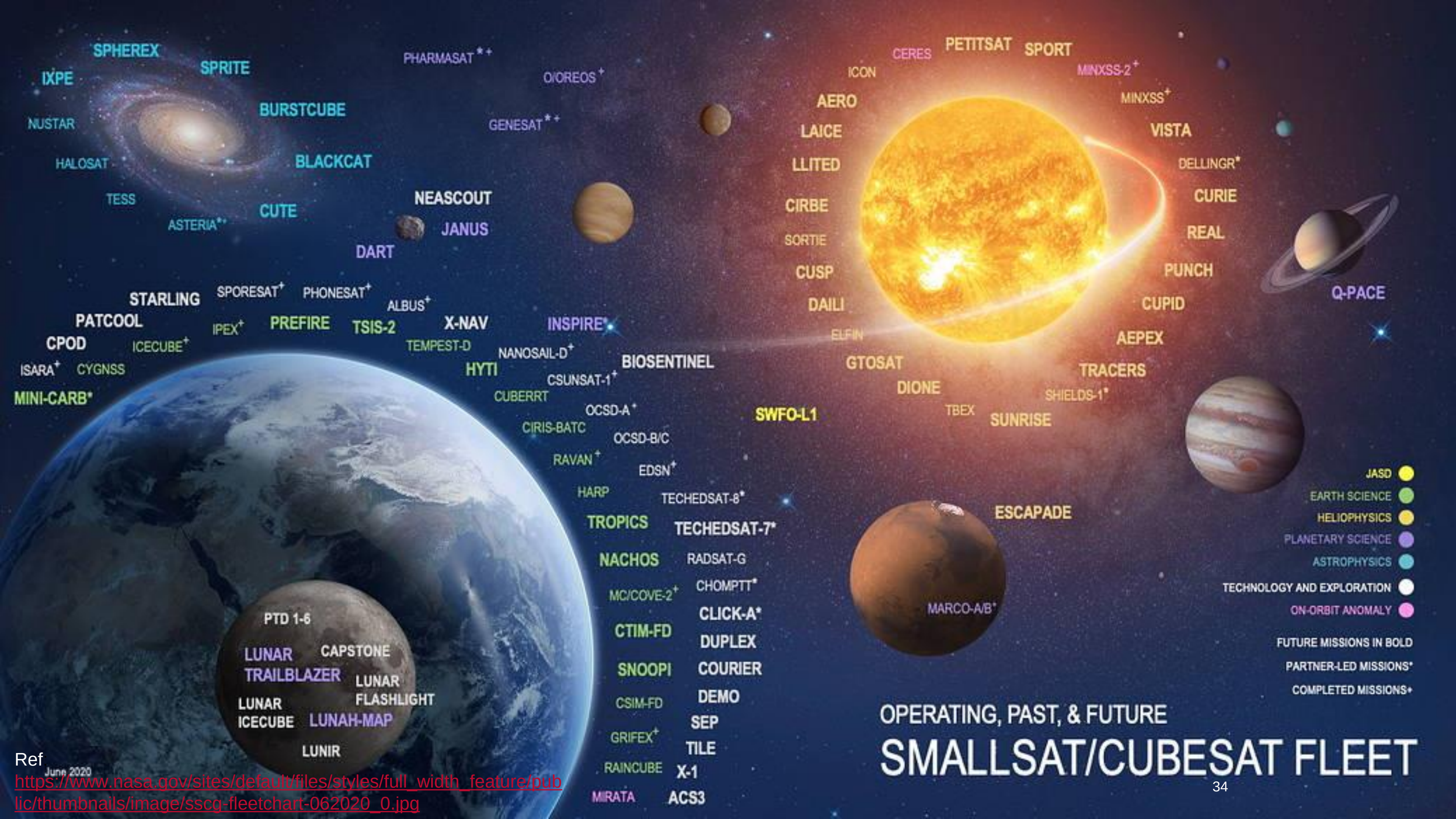
Sporesat (3U), 5 kg



TechEdSat 8 (1x6U), ~8 kg



Cygnss, Microsats, ~30 kg each



Ref
https://www.nasa.gov/sites/default/files/styles/full_width_feature/public/thumbnails/image/sscg-fleetchart-062020_0.jpg

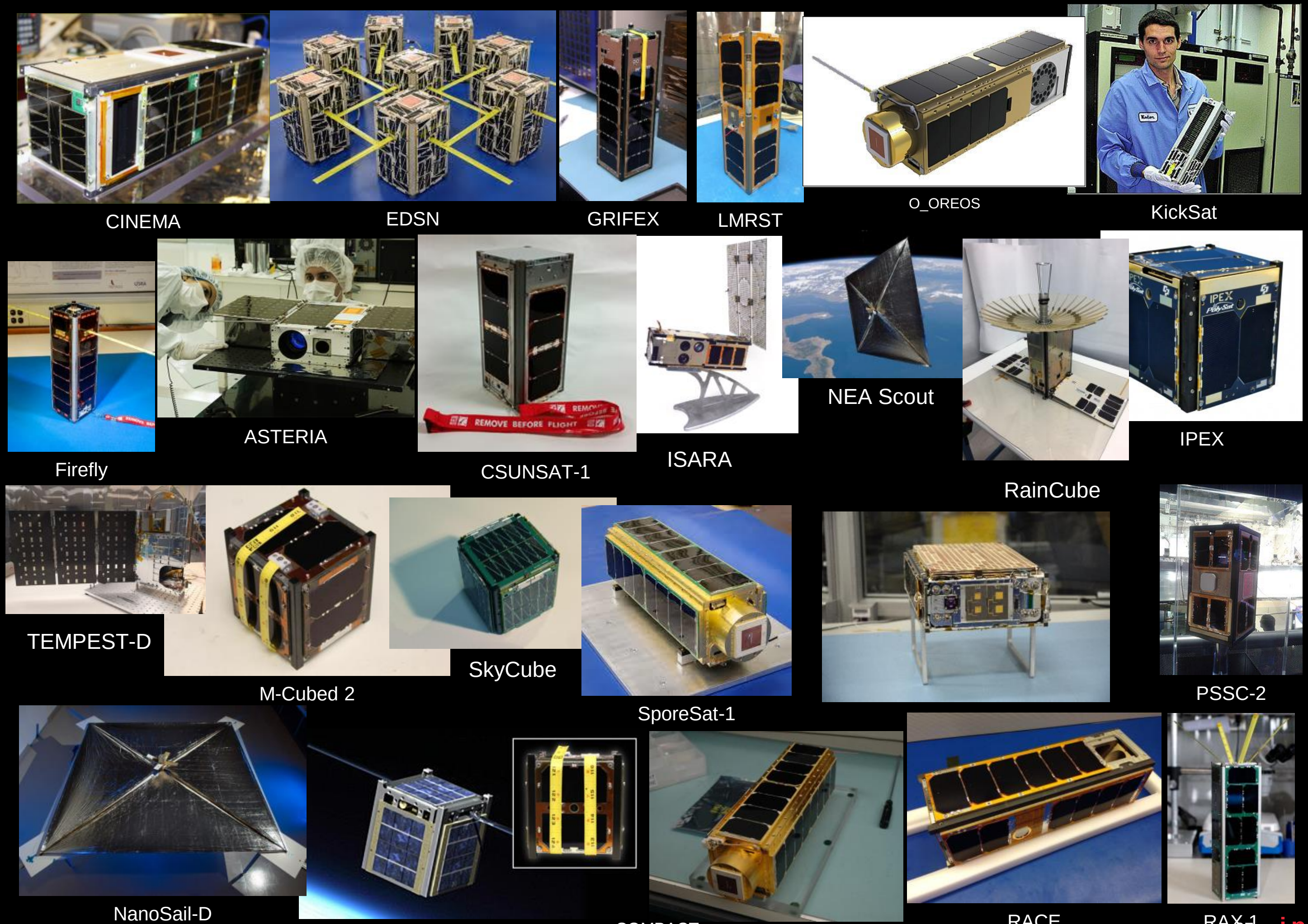
The need for a cubesat/microsat cost model tool

How Does COMPACT fit within the need?

- NASA CubeSat Or Microsat Probabilistic Analogy Cost Tool (COMPACT)
- Official NASA agency cost model tool, started 2014
- Estimate cost specifically for cube/micro-sat class missions
- Providing confidence on cost estimate as model is based on normalized actual NASA funded cubesat/microsat missions

Why do we need a CubeSat/MicroSat cost model?

- Microsat Cost model?
  - Early cost estimation and sanity check
  - Keep projects from over running and under funded
  - Common misconception that costs scales with size of flight system
  - Many cost models has many tuning knobs/switch that will lower the costs, but how real is that to actual design and development practice? How do you defend the basis of estimate (BOE)?


CINEMA
EDSN
GRIFEX
LMRST
O_OREOS
KickSat
Firefly
ASTERIA
CSUNSAT-1
ISARA
NEA Scout
RainCube
IPEX
TEMPEST-D
M-Cubed 2
SkyCube
SporeSat-1
PSSC-2
NanoSail-D
M-Cubed
COMPACT
PharmaSat
RACE
RAX-1

Key Cubesat Data

CubeSat	Launch Date (Actual or Planned)	Mission Type	Developer Type	# U's	Mass (kg)	Power (W)	Development Schedule (B/C/D)	Design Life (months)
ASTERIA	8/14/2017	Science	JPL	6	11	20	28	3
CINEMA (1)	9/13/2012	Science	University	3	3.15	2.9	44	12
CSUNSat-1	4/18/2017	Educational	University	2	2	4		
DHFR	8/26/2017	Tech Demo	JPL	3	5.03	10		3
EDSN	11/3/2015	Tech Demo	Civil	1.5	2	1	10	24
Firefly (1)	11/20/2013	Science	Civil	3	3.51	3.62	36	3
GRIFEX	1/31/2015	Tech Demo	JPL	3	4			
ISARA	11/10/2017	Tech Demo	JPL	6	5	56	48	5
KickSat (1)	4/18/2014	Tech Demo	University	3	6		4	24
LMRST	10/8/2015	Tech Demo	JPL	3	4.6	8		
MarCO	5/5/2018	Tech Demo	JPL	6	12.7	64	21	6.5
M-Cubed	10/28/2011	Tech Demo	University	1	1	1.2	30	
M-Cubed2	12/5/2013	Tech Demo	University	1	1	1.2		
NanoSail-D (2)	11/20/2010	Tech Demo	Civil	3	4			4
NEA Scout	7/1/2018	Tech Demo	JPL and MSFC	6	12.3	50		
O/OREOS	5/19/2009	Science	Civil	3	5.2		12	18
PharmaSat (1)	5/19/2009	Science	Civil	3	5			
PolySat (CP8) "IPEX"	12/5/2013	Tech Demo	University	1	1	1.5	24	6
PSSC-2	7/10/2011	Tech Demo	Civil	2	3.7	5	6	
RACE	10/28/2014	Tech Demo	JPL	3	5	1.5		
RainCube	5/20/2018	Tech Demo	JPL	6	12	35	17	2
RAX 1 (USA 218)	11/20/2010	Science	University	3	3	8		12
SkyCube	1/9/2014	Educational	Commercial	1	1.3	4	24	3
SporeSat-1	4/18/2014	Tech Demo	Civil	3	5.2		36	2
Tempest-D	2/1/2018	Tech Demo	JPL	6	14	21	21	3

CubeSat Cost Estimating Approaches

- Using the data collected in the previous effort, we examined 2 cost estimation approaches and web base platform development:

1. K-Nearest Neighbors (k-NN) – Completed
2. Parametric Cost Modeling – Sneak Peak
3. Web base platform development – Sneak peak

K-Nearest Neighbors

- Created a K-Nearest Neighbors Analogy-drive cost model for CubeSats utilizing the framework developed by the NASA Analogy Software Cost Tool (ASCoT) Team
- Demo and pre-Beta version working its way to the NASA ONCE website (at the time of this presentation)

K-Nearest Neighbors

- KNN is a simple form of analogy cost estimation. Here's how it works:

User Inputs

- Mass (kg)
- # of U's
- # of Spacecraft
- Developer type (university, commercial, civil, JPL)

Find K "closest" observations in historical data

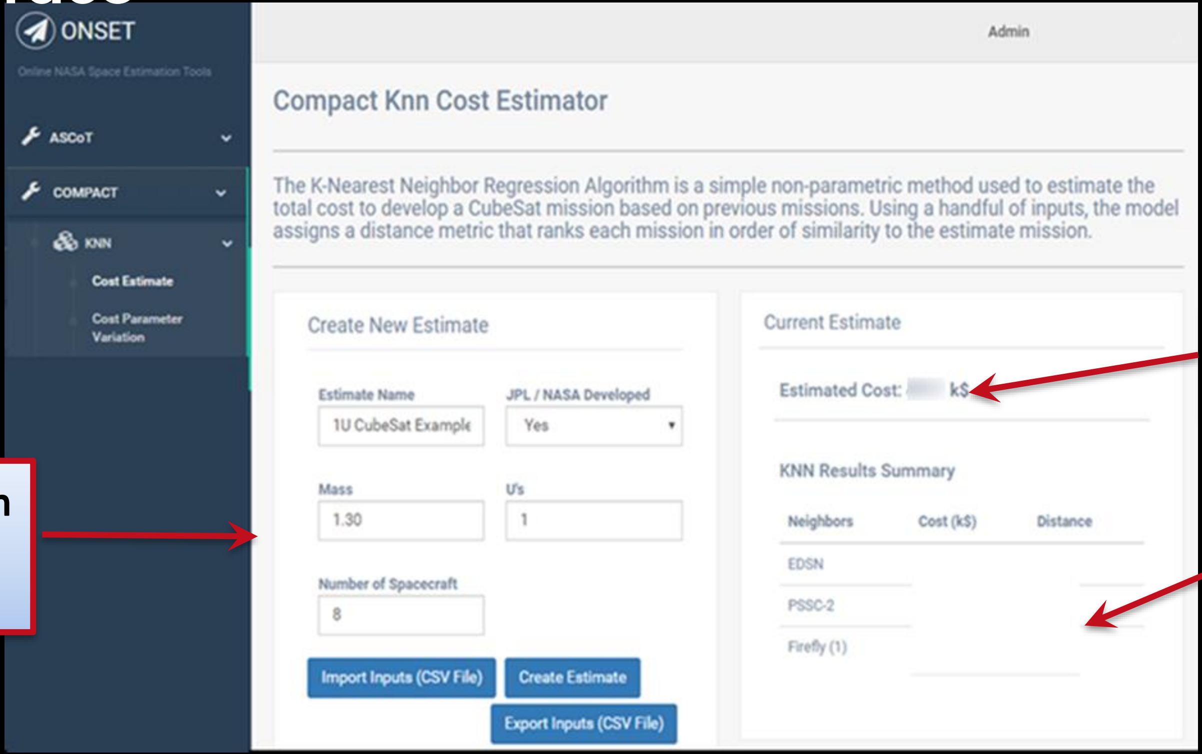
Calculate weighted average of those K costs

Algorithm Outputs

- Names of K most similar CubeSats
- Cost estimate for set of inputs

"Closest" here is determined by Euclidean distance between points. Now, the only thing left to do is to choose the number of neighbors, K.

K-Nearest Neighbors Web Tool
User interface



Output Estimate

Early known high level Input parameter

Analogies

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K-Nearest Neighbors Web Tool Distance

Results: Estimated Cost Compared to Nearest Neighbors and all other Missions

Results by Euclidian Distance

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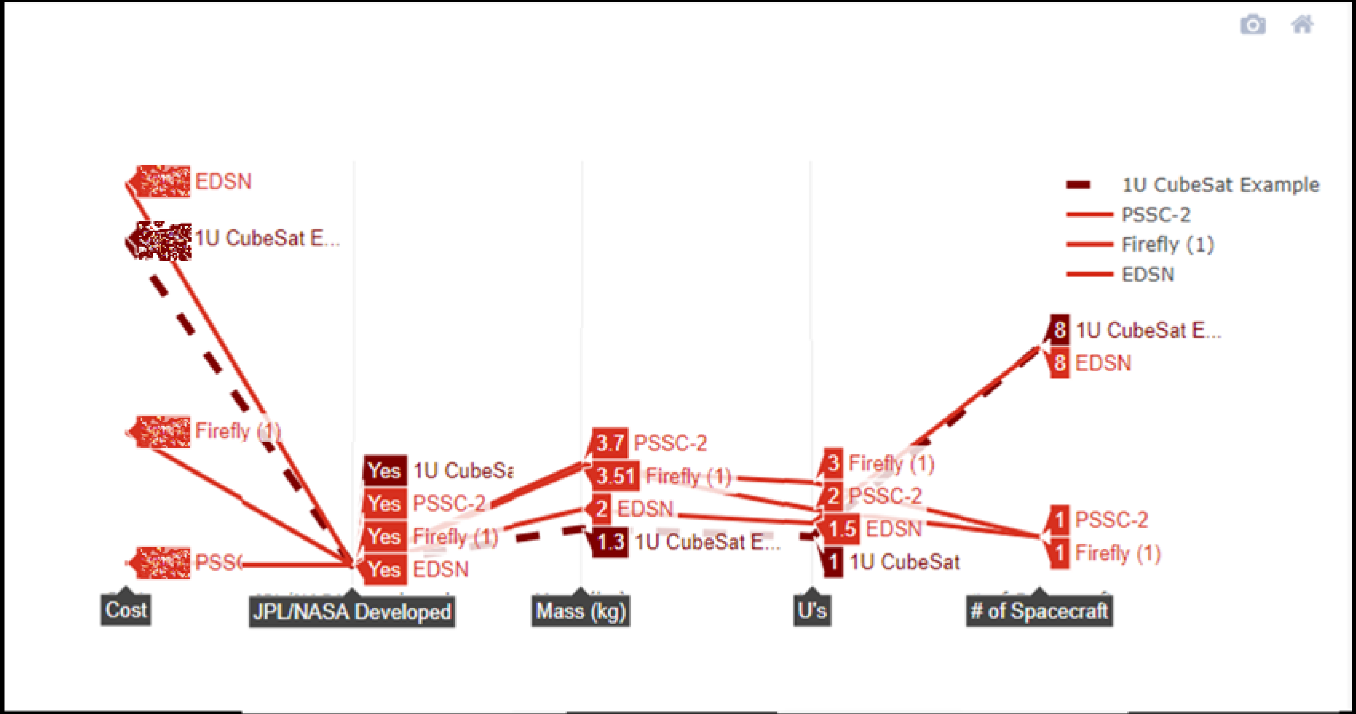
K-Nearest Neighbors Web Tool
Parameter Variation



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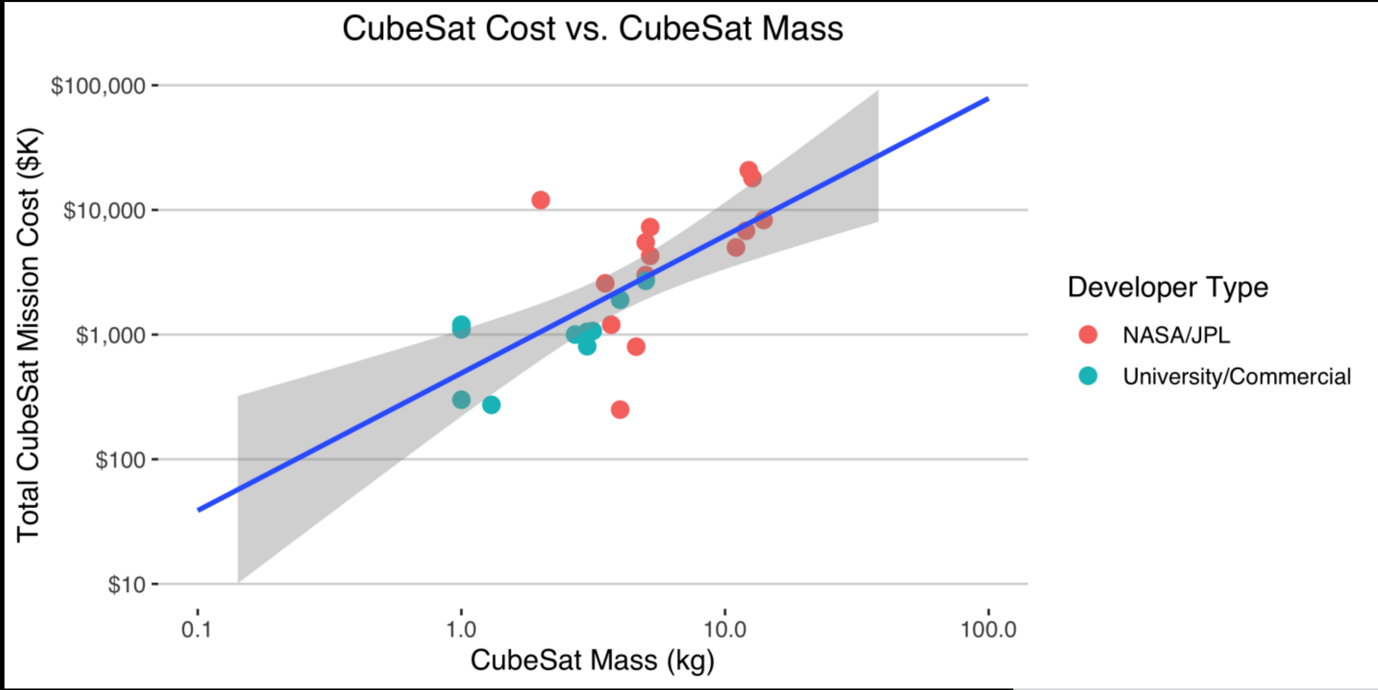
Parametric Models – Sneak Peak

- Apply stepwise and best-subsets regression methods to identify potential CubeSat parametric cost models.

- Utilize ANOVA, standard significance tests and R2 to identify potential cost drivers and compare/select best models.

Draft Preliminary Beta Candidate Model #1

AKA "Not ready for use in Proposal Development/Evaluation"

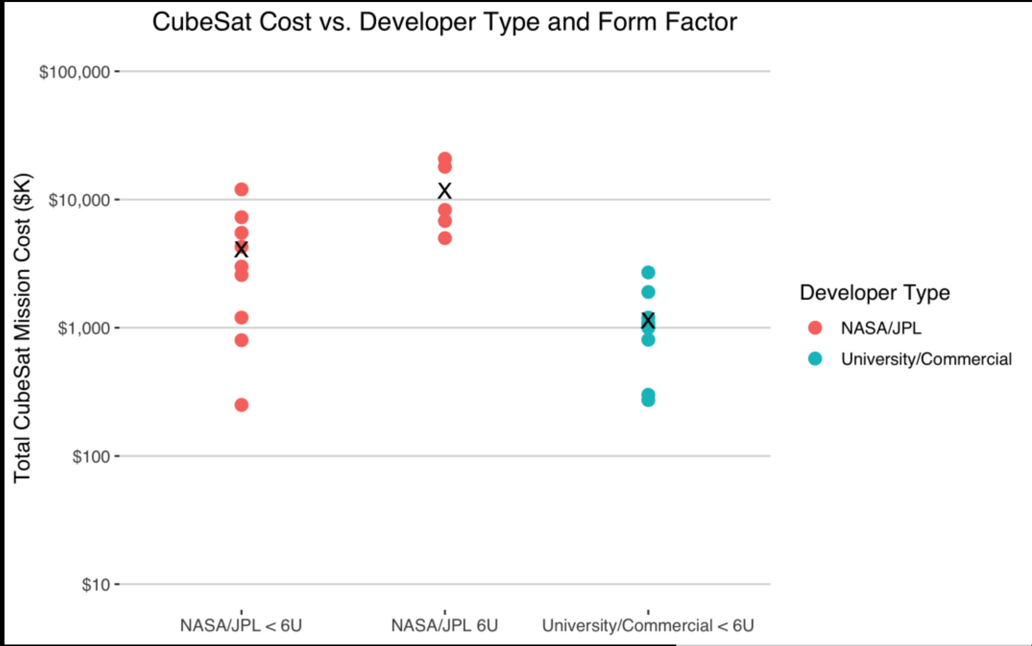


Adjusted R^2: 46%

$$Cost = 491(Mass)^{1.102}$$

Draft Preliminary Beta Candidate Model #2

AKA "Not ready for use in Proposal Development/Evaluation"



Adjusted R^2: 47%

$$Cost = \begin{cases} \$4{,}098 & if < 6U \ \& \ NASA/JPL \\ \$11{,}780 & if\ 6U \ \& \ NASA/JPL \\ \$1{,}140 & if < 6U \ \& \ Univ/Comm \end{cases}$$

NASA COMPACT Cost Model Tool

- Division Director, J. Craig McArthur, NASA HQ Strategic Investment Division (SID)

- Questions in regards to COMPACT directed to NASA HQ Sponsor, contact james.k.johnson@nasa.gov

- Thank you to SID for funding the COMPACT tool development. SID has also funded most/all (research/development) cost tools used across NASA agency wide

- Ref to conference papers and presentation:
  - "COMPACT KNN: Developing an Analogy-Based Cost Estimation Model for CubeSats", IEEE 2020, Big Sky, Montana
  - COMPACT – NASA Cost and Schedule Symposium, 2015, 2016, 2017, 2018, and 2019 (NASA OCFO's website)

Conclusion - Recommendation when cost estimating for Small Missions

Top 10 things on cost estimation

1. Be Realistic
2. Seek help when needed (sooner the better)
3. Treat cost parameter like engineering parameter such as mass and power
4. Not all costs scales with size of the spacecraft
5. Capturing small sat market trend is challenging. Understanding data will guide to better decision making and understanding risks and design decision
6. Risk analysis – factor in uncertainty
7. There's no such thing as one size fits all cost model. Generate multiple estimates using different models and see what the range of variance are and try to understand the *Why* if there is a huge disconnect
8. Defend your cost estimate with a strong basis of estimate
9. Cost estimating is a form of *art* and *science.* There's no right/wrong way to do it, but use good judgement
10. "*There are only two objectives in Formulation. To win, and to not regret it when you do.*" – by Dr. Alfred Nash, JPL Principle Engineer and TeamX Lead

QUESTIONS

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov