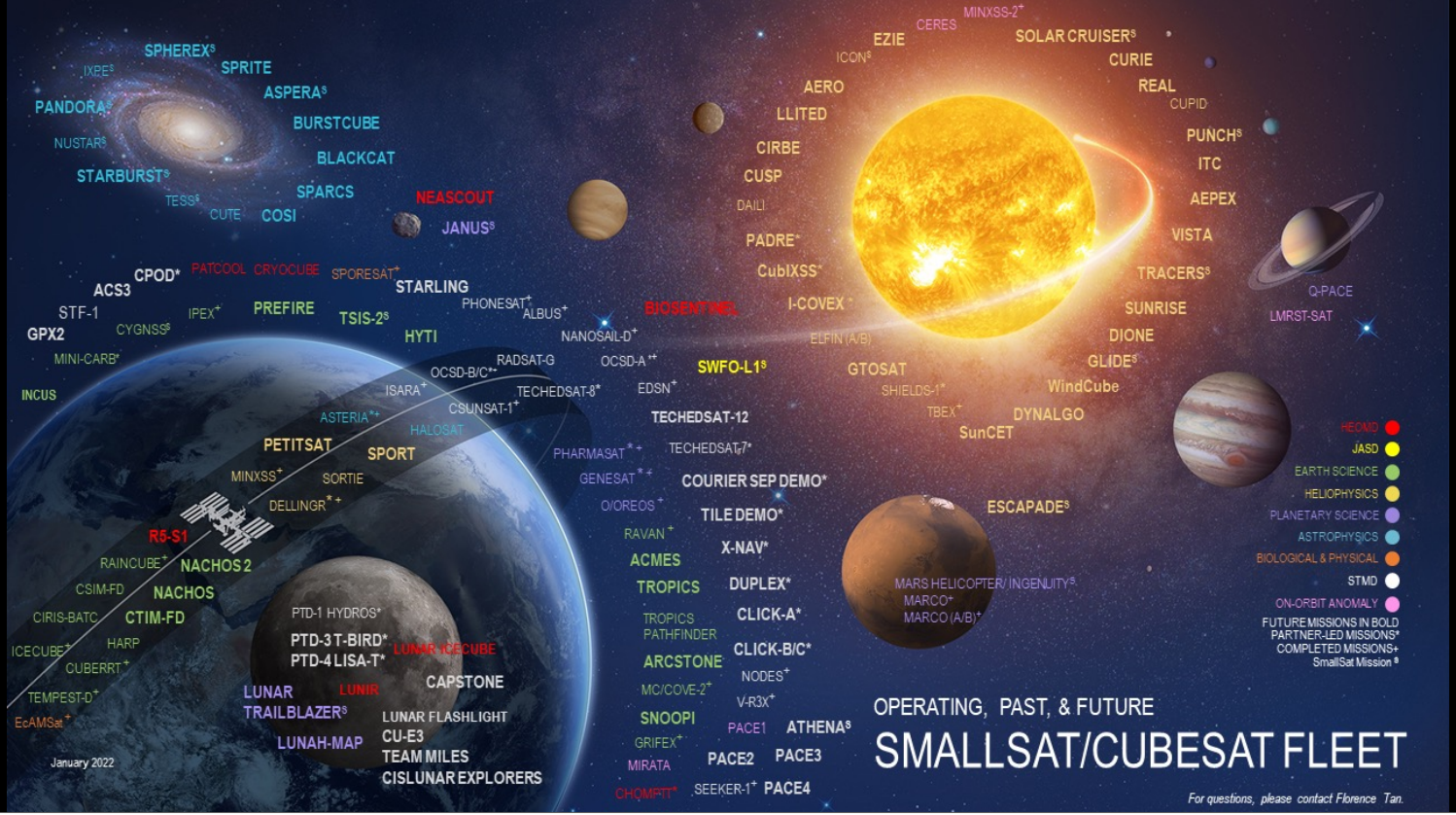


COMPACT KNN V2:

Analogy-Based Cost Estimation Model for CubeSats

Melissa Hooke

April 27, 2022
2022 NASA Cost & Schedule Symposium

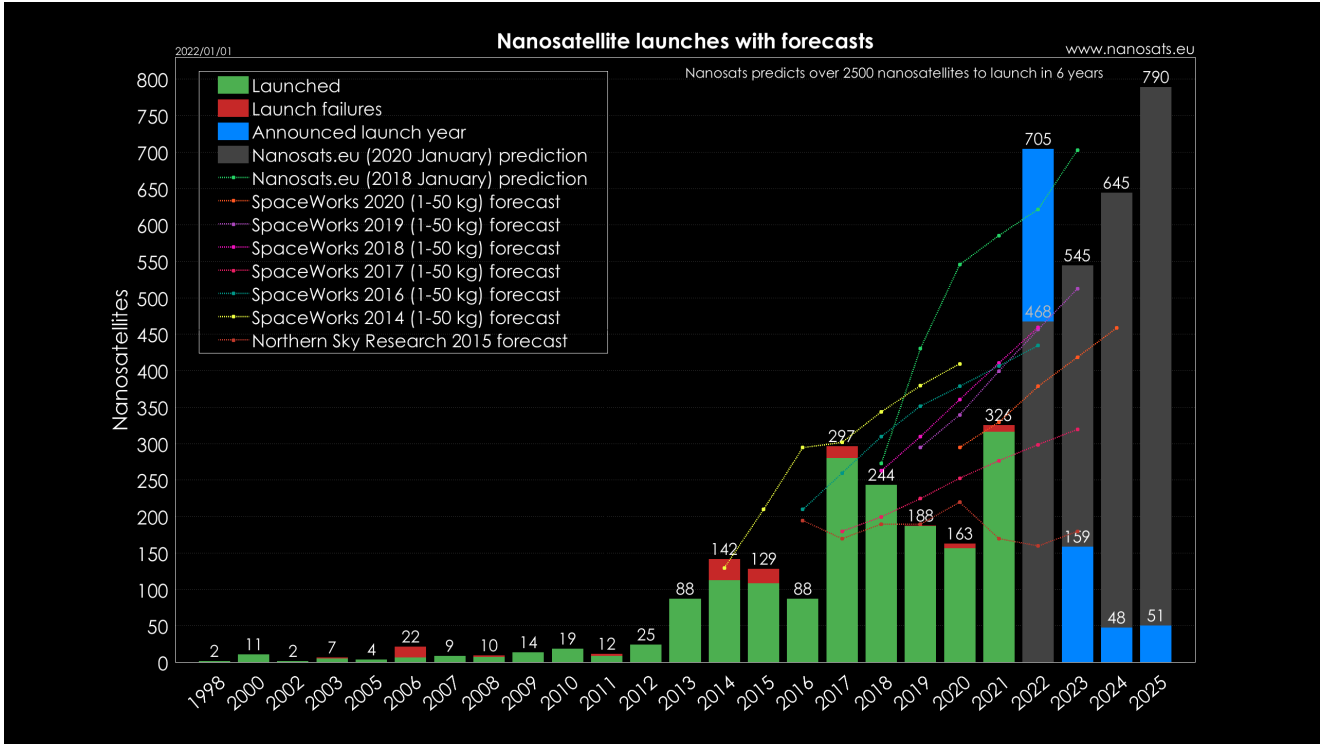
Jet Propulsion Laboratory
California Institute of Technology

Agenda

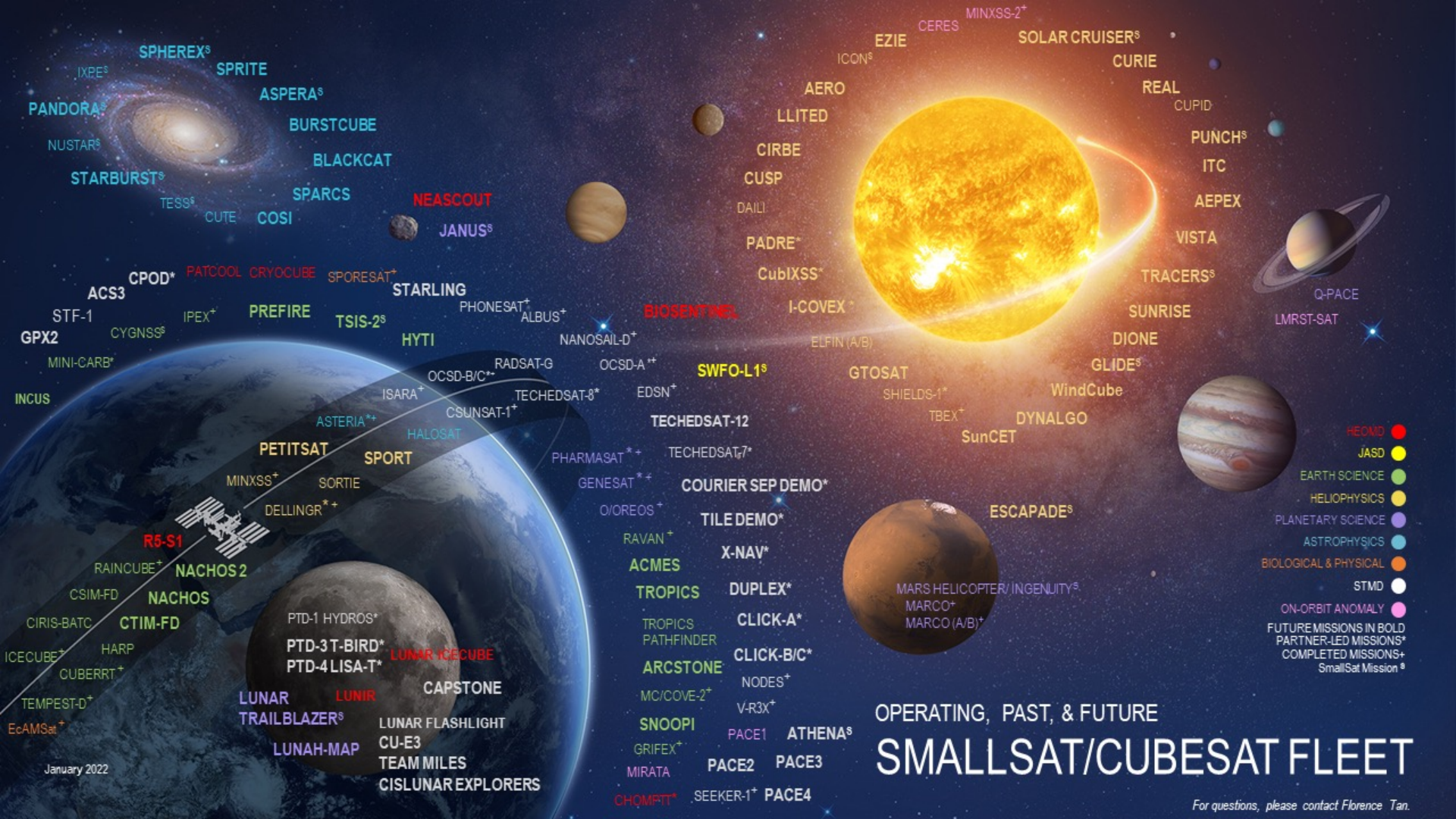
CubeSat Or MicroSat Probabilistic and Analogies Cost Tool (COMPACT)

- Background & Data Collection
- Formalizing Analogy Estimation using KNN
- COMPACT V1 (2019) → COMPACT V2 (2022)
- COMPACT V2
  - Data Updates
  - Model Updates
  - Model Fitting & Validation
- Future Work

The Number of CubeSats/MicroSats is Still Growing!

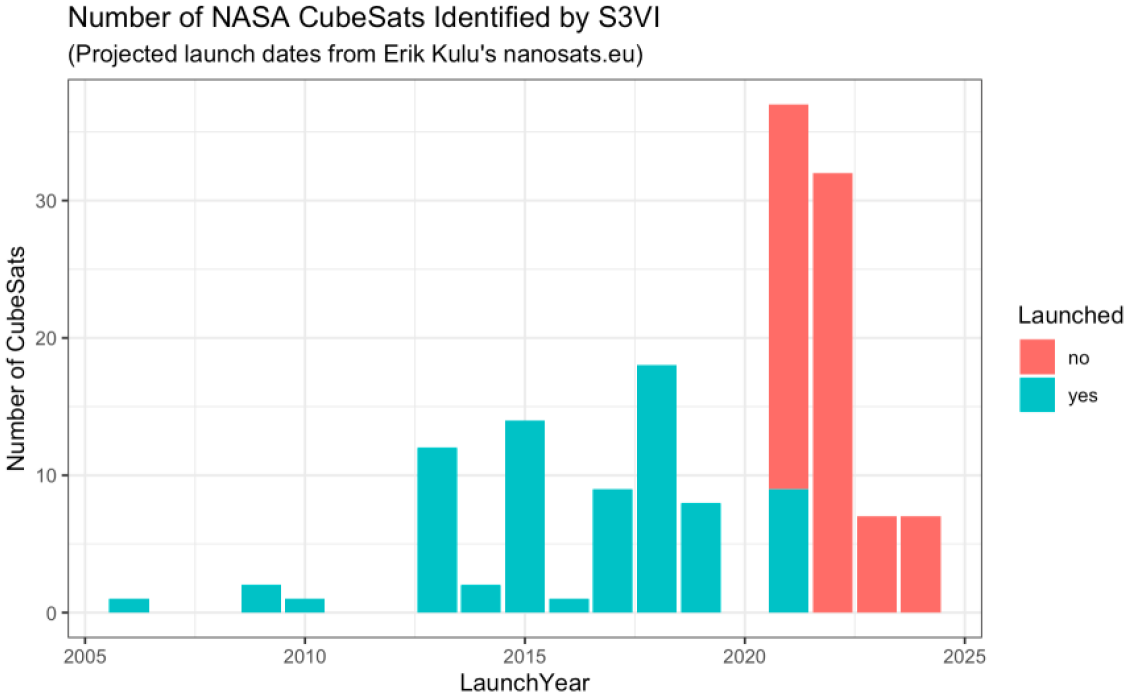


- Each satellite is counted in this plot, rather than counting by constellation
- Nanosats.eu predicts 468 CubeSats/MicroSats to launch in 2022
- This number is dominated by commercial constellations… what about the number of NASA satellites?


SPHEREX§
IXPE§
SPRITE
ASPERA§
PANDORA§
BURSTCUBE
NUSTAR§
BLACKCAT
STARBURST§
SPARCS
TESS§
CUTE
COSI
NEASCOUT
JANUS§
CPOD*
PATCOOL
CRYOCUBE
SPORESAT+
ACS3
STARLING
STF-1
IPEX+
PREFIRE
TSIS-2§
PHONESAT+
ALBUS+
GPX2
CYGNSS§
HYTI
NANOSAIL-D+
MINI-CARB*
RADSAT-G
OCSD-B/C*+
OCSD-A*+
INCUS
ISARA+
TECHEDSAT-8*
EDSN+
CSUNSAT-1+
ASTERIA*+
HALOSAT
PETITSAT
SPORT
MINXSS+
SORTIE
DELLINGR*+
R5-S1
RAINCUBE+
NACHOS 2
CSIM-FD
NACHOS
CIRIS-BATC
CTIM-FD
ICECUBE+
HARP
CUBERRT+
TEMPEST-D+
EcAMSat+
January 2022
PTD-1 HYDROS*
PTD-3 T-BIRD*
PTD-4 LISA-T*
LUNAR ICECUBE
LUNAR
LUNIR
CAPSTONE
TRAILBLAZER§
LUNAR FLASHLIGHT
LUNAH-MAP
CU-E3
TEAM MILES
CISLUNAR EXPLORERS
MINXSS-2+
CERES
EZIE
SOLAR CRUISER§
ICON§
CURIE
AERO
REAL
CUPID
LLITED
CIRBE
PUNCH§
CUSP
ITC
DAILI
AEPEX
PADRE*
VISTA
CubIXSS*
TRACERS§
Q-PACE
BIOSENTINEL
I-COVEX*
SUNRISE
LMRST-SAT
ELFIN (A/B)
DIONE
GLIDE§
SWFO-L1§
GTOSAT
WindCube
SHIELDS-1*
TBEX+
DYNALGO
SunCET
TECHEDSAT-12
PHARMASAT*+
TECHEDSAT-7*
GENESAT*+
COURIER SEP DEMO*
O/OREOS+
TILE DEMO*
ESCAPADE§
RAVAN+
X-NAV*
ACMES
TROPICS
DUPLEX*
MARS HELICOPTER/ INGENUITY§
MARCO+
MARCO (A/B)+
TROPICS PATHFINDER
CLICK-A*
CLICK-B/C*
ARCSTONE
NODES+
MC/COVE-2+
V-R3X+
SNOOPI
PACE1
ATHENA§
GRIFEX+
MIRATA
PACE2
PACE3
CHOMPTT*
SEEKER-1+
PACE4
HEOMD
JASD
EARTH SCIENCE
HELIOPHYSICS
PLANETARY SCIENCE
ASTROPHYSICS
BIOLOGICAL & PHYSICAL
STMD
ON-ORBIT ANOMALY
FUTURE MISSIONS IN BOLD
PARTNER-LED MISSIONS*
COMPLETED MISSIONS+
SmallSat Mission §
OPERATING, PAST, & FUTURE
SMALLSAT/CUBESAT FLEET
For questions, please contact Florence Tan.

The Number of NASA CubeSats is Growing Too

- 82 planned future NASA CubeSats on 56 missions in development
  - vs. 77 launched CubeSats on 57 missions that have launched since 2006
- Some projected launch dates have not been updated, hence tall red bar for 2021



Despite this growth, there was no CubeSat data collection effort or cost estimation capability prior to COMPACT…

COMPACT Data Collection & Normalization

Data Collection Questionnaire

- Short table for PM/PI to fill out with basic mission information that could lead to cost drivers

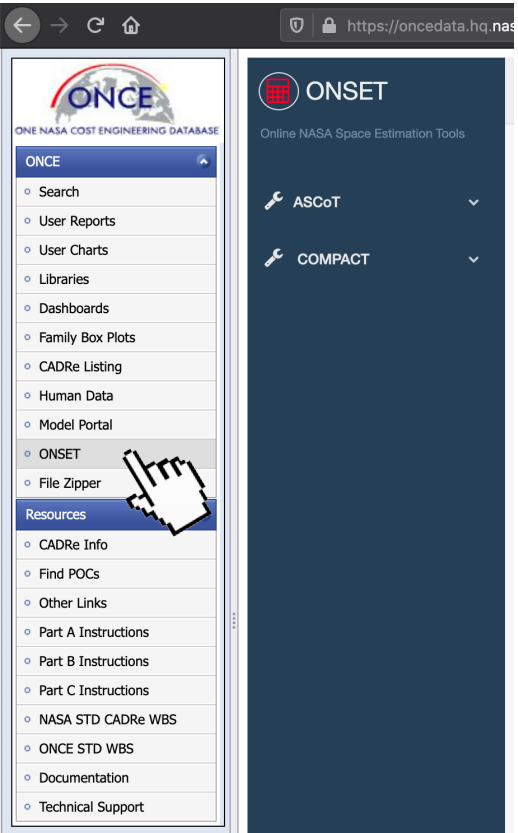
CubeSat Name	
# of U's	
Total Mass (kg) per CubeSat	
# of CubeSats developed/launched	
Peak Power (W) per CubeSat (provide draw and capability, if possible)	
Average Power (W) per CubeSat (specify orbit average or nominal)	
# of Science Instruments per CubeSat	
Design Life (Months from launch to end of primary mission)	
Total Development Schedule (Months from ATP to Pre-ship review)	
Total Mission Cost (Development + Operations)	
Fiscal Year of Cost	
Primary Developer	
Sponsor Organization and/or Partnering Organizations	
NASA Implementation Type (7120.5 / 7120.8 / DNH)	
CubeSat Website	
Operational Status/Mission Success?	

Normalization Process

- Using the data from the questionnaires, our team standardizes each data point:
  - Does the mass & power make sense given the form factor?
  - Are there any costs that may have been overlooked or accounted for somewhere else?
- Big thank you to our normalization team!
  - Andy Klesh, Joe Mrozinski, Mike Saing, Shannon Statham

COMPACT V2 is Live on ONCE via ONSET!

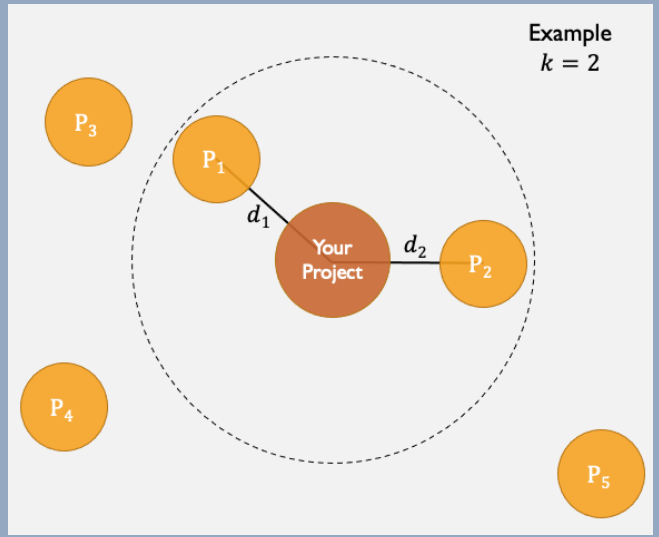
ONSET = Online NASA Space Estimation Toolkit



- Accessible to anyone with access to ONCE - One NASA Cost Engineering Database (https://oncedata.hq.nasa.gov/)
- Core philosophy: transparency of all models and data
- Easy database management
- Backend built using Dash & Django (Python)
  - Easily extends to contain more web-based cost tools
  - Widely used for web development across industries
  - Easy to learn, use, and maintain
- Currently contains COMPACT and ASCoT
  - COMPACT = CubeSat or MicroSat Probabilistic and Analogies Cost Tool
  - ASCoT = Analogy Software Cost Tool
- Latest version is always accessible
- Easy to use on any platform

Formalizing Analogy Estimation using KNN

How does k-Nearest Neighbors (KNN) work?



$$\text{Cost(Your Project)} = \frac{\frac{\text{Cost}(P_1)}{d_1} + \frac{\text{Cost}(P_2)}{d_2}}{\frac{1}{d_1} + \frac{1}{d_2}}$$

- Formalization of analogic cost estimation process using Euclidean distance as “similarity” metric
- Intended for early-on, ballpark cost estimates
- Cost drivers: # U, Mass, Developer Type (NASA/JPL vs. Other)
- Cost estimate is a weighted average of the k most similar missions
  - Weighted by the inverse of the distance (i.e. closer missions have more weight)
- Returns the nearest neighbors for analogy purposes
  - Users can judge whether analogues are appropriate

COMPACT V1

Live on ONCE via ONSET as of late 2019

Accomplishments

- ✓ First widely-available NASA CubeSat cost estimation model
- ✓ Formalized analogy cost estimation process for CubeSats
- ✓ Returned analogy missions

Shortcomings

- ❑ N=24 < number of previously launched NASA CubeSat missions
- ❑ Weighting of all parameters as equal is not appropriate
  - ❑ Correlation between inputs (e.g. mass, # U)
  - ❑ Number of spacecraft parameter not treated as a scaling factor
  - ❑ Questions about interpretability of the distances

COMPACT ~~V1~~ V2

Live on ONCE via ONSET as of ~~late 2019~~ NOW!

Accomplishments

- ✓ First widely-available NASA CubeSat cost estimation model
- ✓ Formalized analogy cost estimation process for CubeSats
- ✓ Returned analogy missions
- ✓ Increases sample size from N=24 to N=34
- ✓ Uses Principal Component Analysis (PCA) to properly weight the cost drivers
  - ✓ Removes correlation between inputs
  - ✓ Number of Spacecraft parameter removed
  - ✓ Distances can be visualized on PCA plot
- ✓ Includes sortable & exportable data tables (cough… ONCE users – this includes cost data!)

Shortcomings

- ❑ N=~~24~~ 34 < number of previously launched NASA CubeSat missions
- ❑ ~~Weighting of all parameters as equal is not appropriate~~
  - ❑ ~~Correlation between inputs (e.g. mass, # U)~~
  - ❑ Number of spacecraft parameter ~~not treated as a scaling factor~~ not included
  - ❑ ~~Questions about interpretability of the distances~~

COMPACT V2

Data Updates

✓Added data from 17 new CubeSat missions, mostly launched in 2018-2019

Added	Removed
AlBus	EDSN
CeReS	LMRST
CIRiS-BATC	M-Cubed/COVE-2
CSIM-FD	MarCO
CUBERRT	NanoSail-D
EcAMSat	NEA Scout
HaloSat	SkyCube
IceCube	
Kenobi	
MiniCarb	
MinXSS-1	
MinXSS-2	
MiRaTa	
RAVAN	
Seeker	
Shields-1	
STF-1	

However, also had to remove some missions:

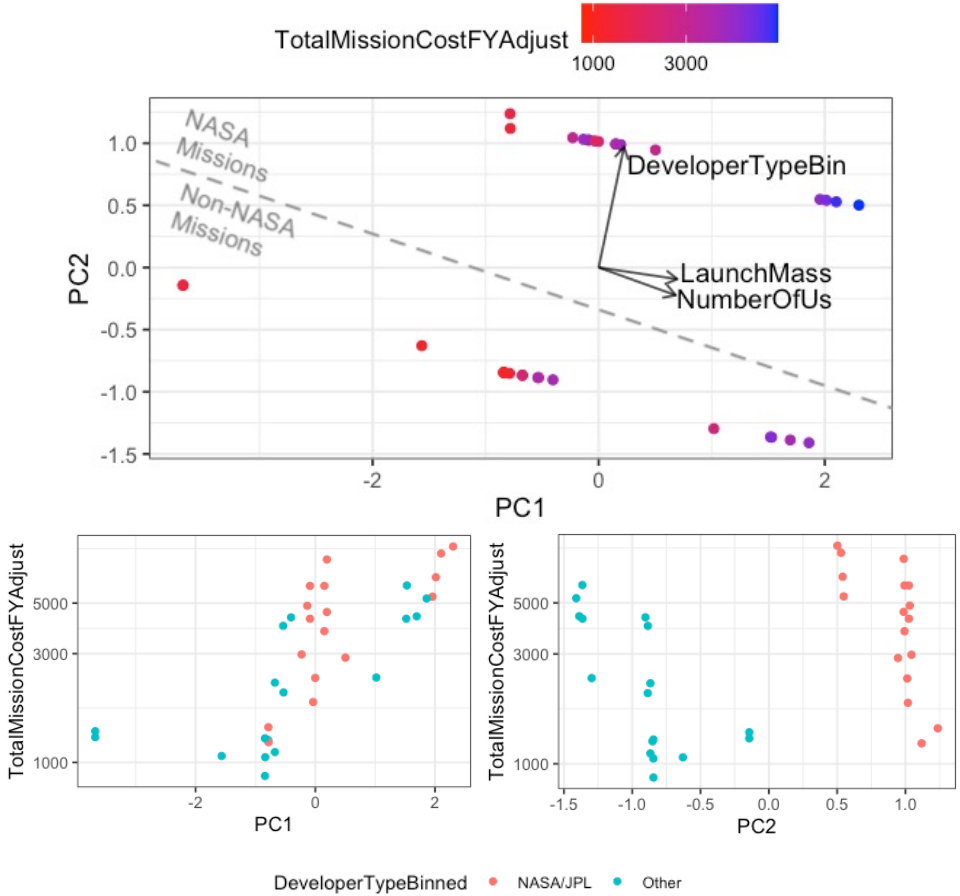
- ✓ Removed Number of Spacecraft parameter & data for CubeSat missions w/ multiple identical spacecraft (EDSN & MarCO)
- Other reasons:
  - LMRST - missing costs due to funding mechanism
  - M-Cubed/COVE-2 & NanoSail-D - modified flight spares
  - NEA Scout - not yet launched
  - SkyCube - developer not applicable

Mission Name	Launch Date	Number Of Us	Mass	Developer Type
CIRiS-BATC	**12/5/19**	**6**	**14.0**	**Other**
MiniCarb	**12/5/19**	**6**	**6.4**	**Other**
Kenobi	**4/17/19**	**3**	**2.1**	**NASA/JPL**
Seeker	**4/17/19**	**3**	**4.2**	**NASA/JPL**
AlBus	**12/16/18**	**3**	**4.0**	**NASA/JPL**
CeReS	**12/16/18**	**3**	**4.3**	**NASA/JPL**
Shields-1	**12/16/18**	**3**	**6.9**	**NASA/JPL**
STF-1	**12/16/18**	**3**	**3.0**	**Other**
CSIM-FD	**12/3/18**	**6**	**10.2**	**Other**
MinXSS-2	**12/3/18**	**3**	**3.5**	**Other**
CUBERRT	**5/21/18**	**6**	**10.3**	**Other**
HaloSat	**5/21/18**	**6**	**12.0**	**Other**
RainCube	5/21/18	6	11.6	NASA/JPL
Tempest-D	5/21/18	6	14.0	NASA/JPL
MiRaTA	**11/18/17**	**3**	**4.5**	**Other**
EcAMSat	**11/12/17**	**6**	**10.7**	**NASA/JPL**
ISARA	11/12/17	3	5.0	NASA/JPL
ASTERIA	8/14/17	6	10.2	NASA/JPL
CSUNSat-1	4/18/17	2	2.7	Other
IceCube	**4/18/17**	**3**	**4.0**	**NASA/JPL**
RAVAN	**11/11/16**	**3**	**4.0**	**Other**
MinXSS-1	**12/6/15**	**3**	**3.5**	**Other**
GRIFEX	1/31/15	3	4.0	Other
RACE	10/28/14	3	3.8	NASA/JPL
SporeSat-1	4/18/14	3	5.2	NASA/JPL
CP8	12/6/13	1	1.0	Other
Firefly	11/20/13	3	3.5	NASA/JPL
CINEMA-1	9/13/12	3	3.2	Other
CSSWE	9/13/12	3	3.0	Other
M-Cubed/COVE	10/28/11	1	1.0	Other
PSSC-2	7/10/11	2	3.7	NASA/JPL
RAX-1	11/20/10	3	3.0	Other
O/OREOS	5/19/09	3	5.2	NASA/JPL
PharmaSat-1	5/19/09	3	5.0	NASA/JPL

COMPACT V2

Model Updates

- ✓ Removed Number of Spacecraft parameter
  - Cost drivers: # U, Mass, Developer Type (NASA/JPL vs. Other)
- Principal Component Analysis (PCA) prior to KNN algorithm
  - ✓ Removes correlation between input parameters
  - ✓ Re-weights parameter space = more interpretability to distances
  - Maintain PC's that explain significant amount of variance in the data while still correlating with cost

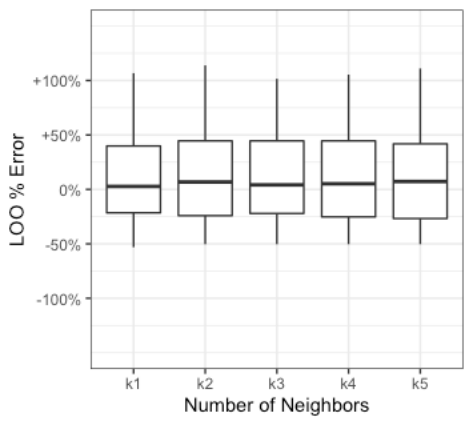


COMPACT V2

Model Fitting & Validation

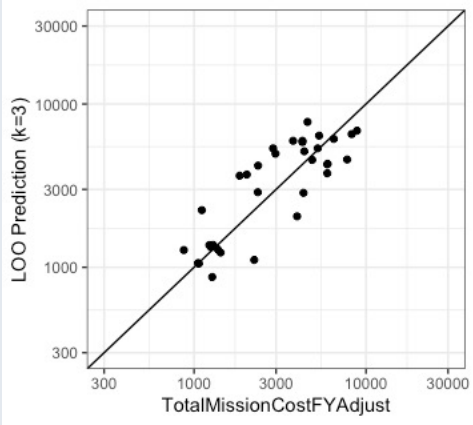
The leave-one-out (LOO) predictions are used as an approximation of out-of-sample performance in order to assess the overall predictive performance of the KNN model.

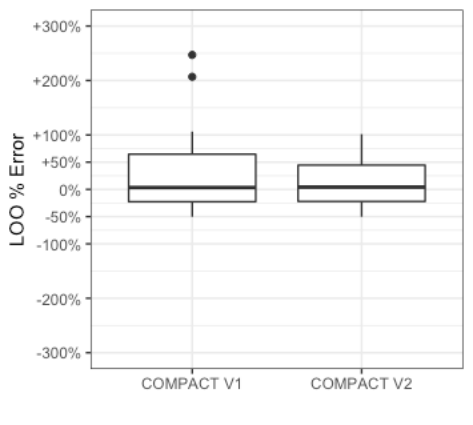
Fitting:



Since the number of neighbors, k, has little impact on the predictive performance of the model; k = 3 was selected as a reasonable number of analogues to return

Validation:





The KNN tool predicts the cost of ~75% of CubeSat missions to within +/- 50% of the actual mission cost. This is improved from 65% in COMPACT V1 w/ 2 missions LOO prediction > 3x the actual cost of the mission

COMPACT Future Work

1. Main focus: continued data collection for recently launched CubeSat missions & tracking future missions
    - Science-focused CubeSat constellations (e.g. SunRise, TROPICS)
    - Beyond-Earth missions (e.g. BioSentinel, Lunar Flashlight, NEA Scout)
2. Continue exploration of non-parametric and parametric cost modeling techniques for the COMPACT data
    - Scaling factors for building multiple identical spacecraft
3. A brand new set of tool features is on the horizon
    - Fiscal year conversion capability
    - Data sheets for analogy information

Jet Propulsion Laboratory
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jpl.nasa.gov