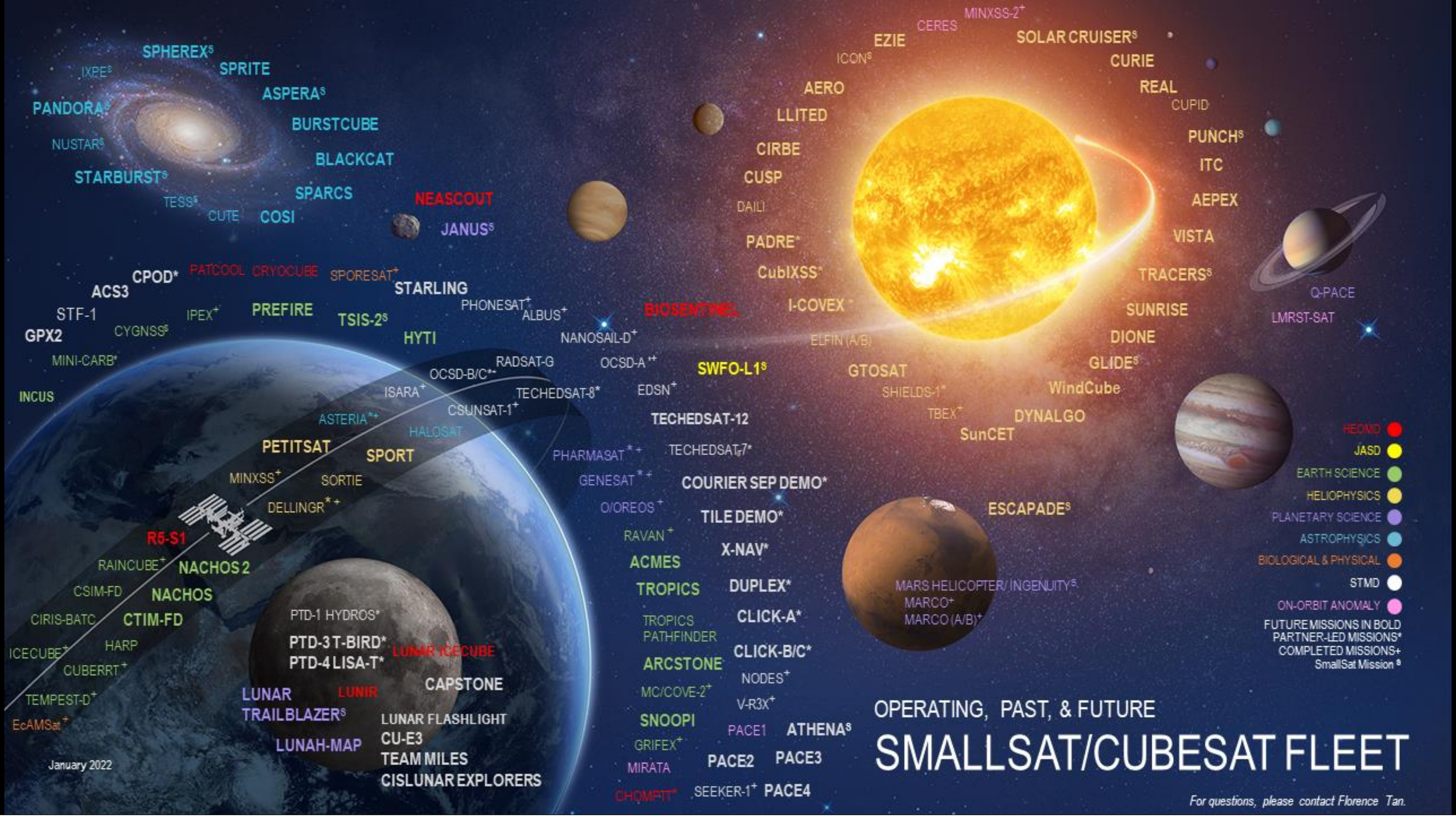

Analogy Cost Estimation for CubeSats using COMPACT

Jet Propulsion Laboratory
California Institute of Technology

2023 NASA Cost & Schedule Symposium (May 2 - 4, 2023)

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Agenda

COMPACT = CubeSat Or MicroSat Probabilistic and Analogies Cost Tool

1. CubeSat Background & COMPACT Data Collection
2. Challenges of Analogy Cost Estimation
3. Formalizing Analogy Estimation using COMPACT KNN
4. New Features to Aid in Analogy Estimation

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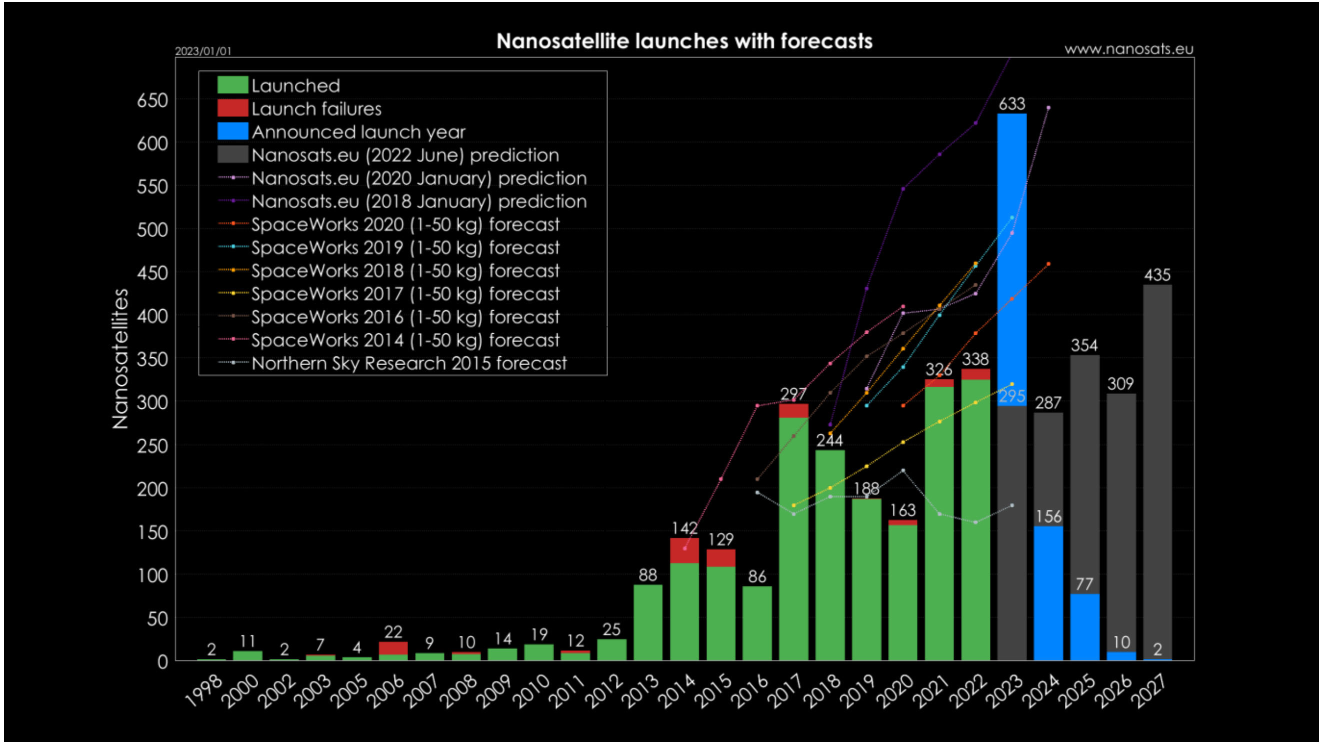
The Number of CubeSats/MicroSats is Still Growing!



- Each satellite is counted in this plot, rather than counting by constellation
- 338 CubeSats/MicroSats were launched in 2022
- This number is dominated by commercial constellations… what about the number of NASA satellites?

Erik Kulu, Nanosats

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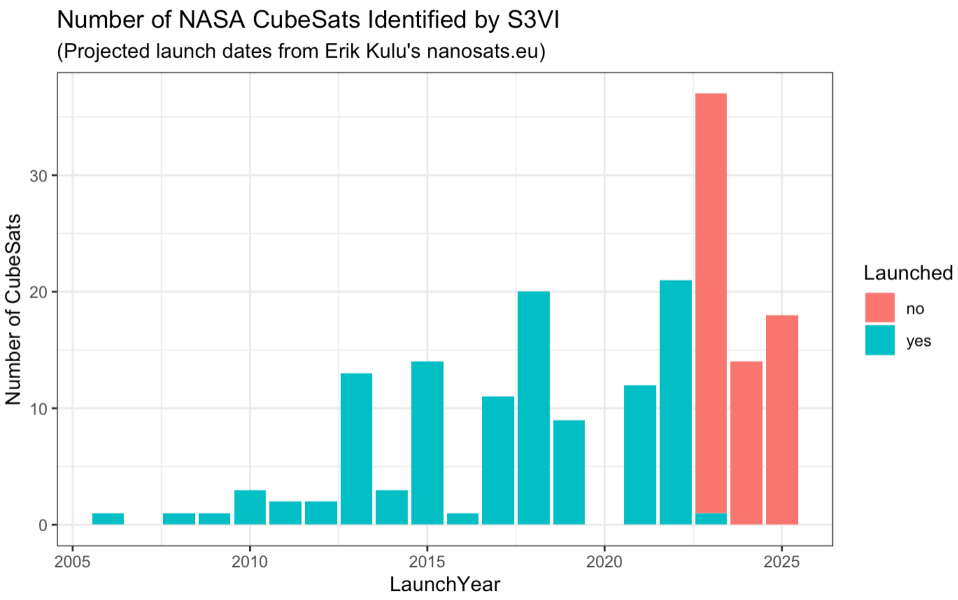
The Number of NASA CubeSats is Growing Too



- 115 CubeSats on 91 missions that have launched since 2006
- 68 planned future NASA CubeSats on 48 missions in development

23 NASA CubeSats Launched in 2022!

BioSentinel	Lunar Icecube
CAPSTONE	LunIR
CLICK-A	NACHOS (2)
CPOD (2)	NEA Scout
CTIM-FD	PAN (2)
CuSP	PetitSat
GPX-2	PTD-3
INCA	SPORT
LunaH-MAP	TROPICS (2)
Lunar Flashlight	
Total Cost	**>$275M**

Names in red indicate launch failure

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COMPACT's Role

COMPACT is the largest NASA CubeSat data collection effort & the only effort which:

1. **Collects and normalizes cost driving parameters by communicating directly with projects**
2. **Develops cost estimation tools that can be used directly by both cost estimators & evaluators**
3. **Shares all data and model development methodology transparently with users**

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CubeSat Data Collection Challenges

- There is no data pipeline for CubeSat cost / technical data
- Public data does not include the full data story
  - Old cost *estimates* are published, rather than cost *actuals*
  - Some costs are contributed - need to compare apples to apples
- Collecting data from missions directly is slow-going
  - People don’t respond or no longer have access to cost records
  - Or, didn’t keep records to begin with
- WBS costs are very difficult to come by or are non-existent
  - Sometimes can’t even break out costs between development vs. operations

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COMPACT Data Collection & Normalization

Data Collection Questionnaire

- Short table for PM/PI to fill out with basic mission information that we see as potential 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?	

*Note: Projects providing data to NASA have agreed to distribution of that data to COMPACT users.

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, Takuto Ishimatsu, Joe Mrozinski, Mike Saing, Shannon Statham

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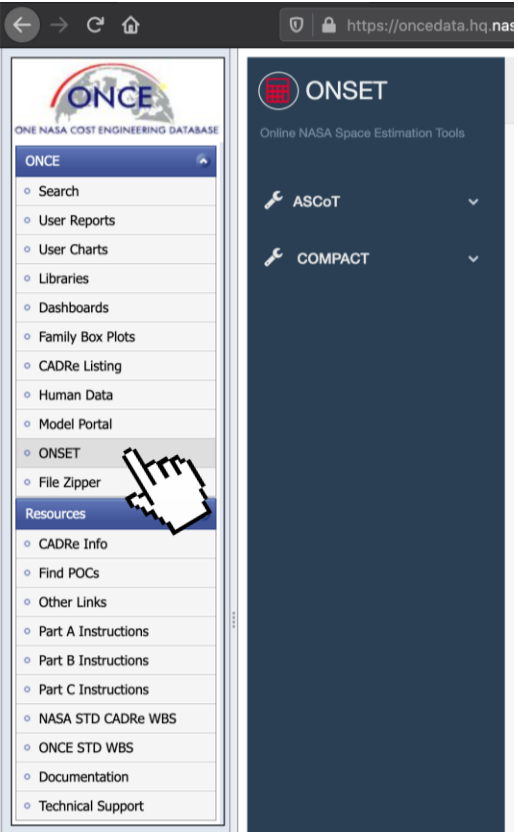
COMPACT V2 is Live on ONCE via ONSET!

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

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A Fun Prediction Experiment

Question: Julie is currently a senior in a state university. She read fluently when she was four years old. What is her grade point average (GPA)?

Answer: You likely responded that Julie's GPA is around a 3.7 or 3.8.

This answer ignores base rates (the average college GPA is a 3.1), and overvalues your intuition about the causal effect of reading early on GPA, leading to overconfidence and bias in your prediction.

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A Fun Prediction Experiment (Cont.)

What happened when you tried to answer that question?

1. Your brain automatically searched for a causal link between the evidence (Julie's reading) and the target of the prediction (her GPA). Concluding that early reading and a high GPA are both indications of academic talent.
2. Associative memory quickly constructed the best possible story from the information available. How precocious is a child who reads fluently at age four? What relative rank or percentile score corresponds to this achievement?
3. Next, you substituted this new question for the original. The evaluation of the flimsy evidence of cognitive ability in childhood is substituted as an answer to the question about her college GPA. Julie will be assigned the same percentile score for her GPA and for her achievements as an early reader.
4. The question specified that the answer must be on the GPA scale, which requires an intensity-matching operation, from a general impression of Julie's academic achievements to the GPA that matches the evidence for her talent.

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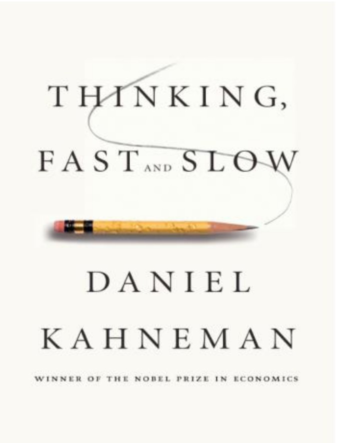
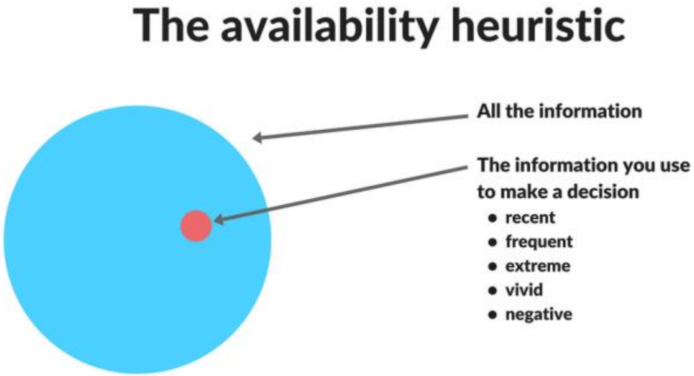
Challenges of Analogy Cost Estimation

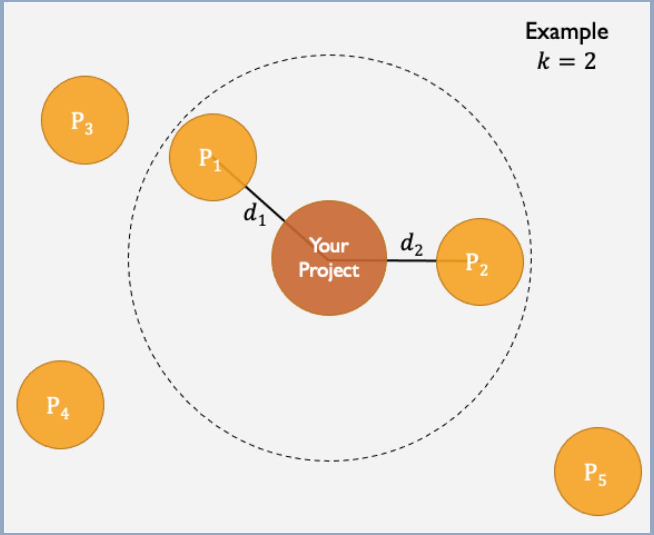


- Ignorance of base rates – e.g. average & variance of mission costs
- Overconfidence / overexaggerating similarity to analogue missions
- “What you see is all there is” – we create coherent stories based on easily available information <u>only</u>
  - Availability heuristic
  - Ignore information that is misaligned with our story
  - Less information => more coherence => overconfidence => understating uncertainty
- Substitution & intensity matching make the task easier, but often warp the original question that we wanted to answer



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

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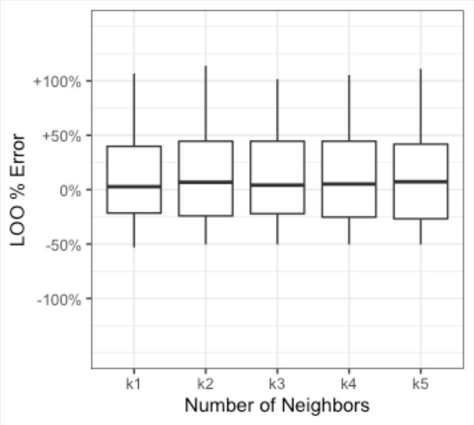
COMPACT V2

Model Fitting & Validation

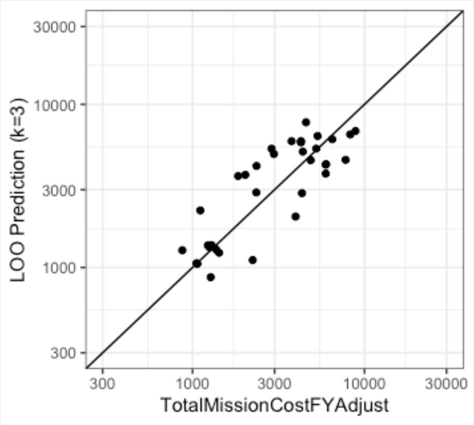
The leave-one-out (LOO) cross-validation predictions are used as an approximation of out-of-sample performance in order to assess the overall predictive performance of the KNN model.

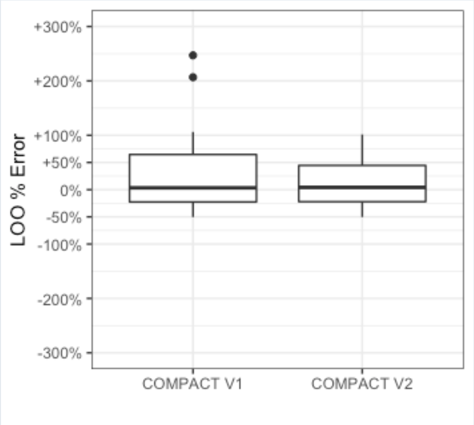
Fitting:



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

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KNN vs. Traditional Analogy Estimation

- Data is all available in one place on the COMPACT tool – allows for calculation of *base rates*
- Less prone to *availability bias,* since there is more information available and the estimation process is formalized and replicable
- Users still have the flexibility to verify & defend the similarity of the analogue missions that are selected
- Model performance is quantifiable
  - Not available for pure analogy estimation since there is no paper trail and method is less rigorous / more variable depending on the estimator

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COMPACT Analogy Estimation Tips

1. Export the data

Mission Name	Launch Date	Cost (FY19 $M)	Developer Type	Mass (kg)	# U's	PC1
CIRiS-BATC	2019-12-05		Other	14	6	1.86013
MiniCarb	2019-12-05		Other	6.4	6	1.01876
Kenobi	2019-04-17		NASA/JPL	2.1	3	-0.78154
Seeker	2019-04-17		NASA/JPL	4.2	3	-0.03649
AIBus	2018-12-16		NASA/JPL	4	3	-0.08893
CeReS	2018-12-16		NASA/JPL	4.34	3	-0.00125
Shields-1	2018-12-16		NASA/JPL	6.94	3	0.50261
STF-1	2018-12-16		Other	3.01	3	-0.83668
CSIM-FD	2018-12-03		Other	10.2	6	1.51975
...						
RAX-1	2010-11-20		Other	3	3	-0.84025
O/OREOS	2009-05-19		NASA/JPL	5.2	3	0.19308
PharmaSat-1	2009-05-19		NASA/JPL	5	3	0.15092

*Note: Mission cost data redacted for public release of these slides. COMPACT users have access to unredacted data via ONCE.

Export

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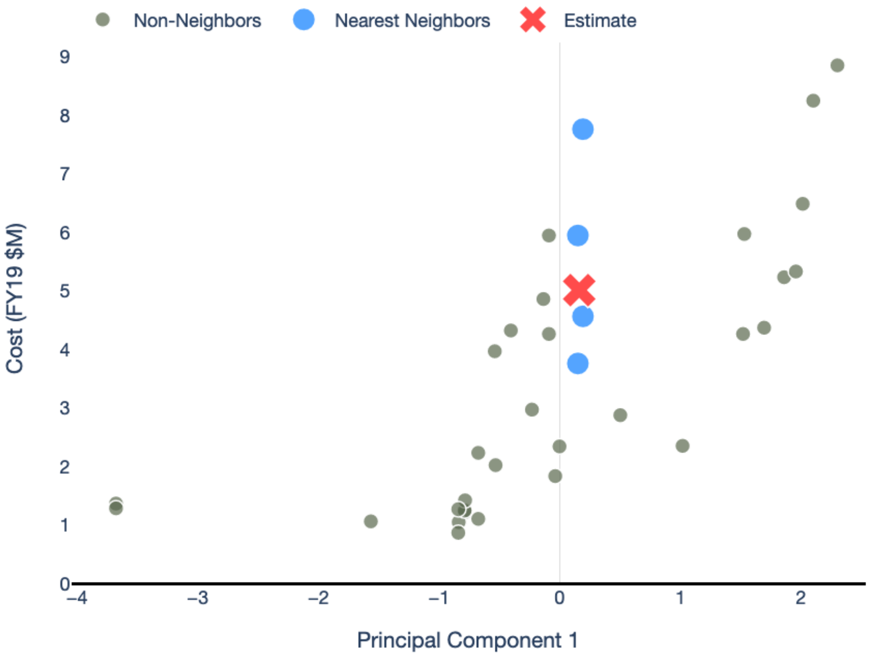
COMPACT Analogy Estimation Tips

2. Use the PCA plot visualization

- PCA reduces dimensions of input space from 3 down to 1
- Distances in KNN space so you can visualize where your input mission falls in relation to flown missions
- Interactive scroll over to see names & costs of nearby missions



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COMPACT Analogy Estimation Tips

3. Check out the mission data sheets

MiniCarb

Mission Overview:

Mission Name Full	Mission Type	Launch Date	Destination Type	Specific Destination	Mission Design Life	Mission Status	Mission Success
CubeSat Next Generation Bus (CNGB)	Science	2019-12-05 00:00:00	Earth Orbiting	-	12	Complete	No

Mission Description
Once in orbit, Mini-Carb will observe the region between the upper troposphere to the lower stratosphere between 9.6 and 29 km above Earth's surface. Measurements in this atmospheric region provide important information about stratospheric circulation and how it responds to increasing greenhouse gas concentrations. cientists believe that the projected increases in methane and carbon dioxide this century will affect several physical processes that drive climate change, she said. Methane, which is especially long-lived, results in the increased production of stratospheric water vapor and hydroxide, which directly affects ozone, the layer that protects Earth from harmful ultraviolet radiation.

Development:

Mission Lead Organization	PM Name	PM Email	PI Name	PI Email	SE Name	SE Email
LLNL	Vincent Riot	riot1@llnl.gov	-	-	-	-

Payload Developer	Bus Provider	Development Partners	Procuring Agency	Program	NASA Implementation Type	Mission Development Schedule
NASA GSFC	LLNL	NASA Goddard (payload)	NASA IRAD	NASA-center	IBP	42

Technical Details:

Number Of U's	Launch Mass (kg)	Peak Power (W)	Average Power (W)	Solar Panels Deployable Or Body Mounted	Number Of Instruments	Number Of Spacecraft Flown
6	6.4	-	13	Deployable	1	1

Cost:

Total Mission Cost (FY19 $M)	Extended Mission Cost (FY19 $M)
redacted	-

WBS 1. PM (FY19 $M)	WBS 2. SE (FY19 $M)	WBS 3. S&MA (FY19 $M)	WBS 4. Science (FY19 $M)	WBS 5. Payload (FY19 $M)	WBS 6. SC (FY19 $M)	WBS 7. MOS (FY19 $M)	WBS 8. Launch (FY19 $M)	WBS 9. GDS (FY19 $M)	WBS 10. SI&T (FY19 $M)
-	-	-	-	-	-	-	-	-	-

Comments & Normalization Assumptions:

Additional Comments

8/31/20 Melissa Hooke:
This entry was created based on information from https://str.llnl.gov/2019-04/riot including a cost figure of $500,000. This number should be verified.

LLNL provided the bus; Goddard provided the payload

The mass (8kg) and power (42W) were estimated based on the following source: https://www.osti.gov/servlets/purl/1605529 which states a mass of <3kg for the instrument and a mass of 5kg for the bus from the source above. The peak power of 42W is based on the following: "maximum theoretical power that can be harvested from the solar cells (cells are theoretically 28% efficient with a 42W maximum expected power)"

*Note: Mission cost data redacted for public release of these slides. COMPACT users have access to unredacted data via ONCE.

Summary: COMPACT

Check it out on ONCE via ONSET!

Accomplishments

- ✓ First widely-available NASA CubeSat cost estimation model
- ✓ Formalizes analogy cost estimation process for CubeSats
- ✓ Returns list of potential analogue missions
- ✓ Current mission sample size, N=34
- ✓ Uses Principal Component Analysis (PCA) to properly weight the cost drivers
  - ✓ Removes correlation between inputs
  - ✓ Distances can be visualized on PCA plot
- ✓ Sortable & exportable data tables (cough… ONCE users – this includes cost data!)
- ✓ New: Mission data sheets include information about analogy missions
- ✓ New: Fiscal year adjustment capability

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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. More features for analogy estimation! Let us know what you want to see added!

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