Small Satellite Reliability: Database Update and Identifying Best Practices

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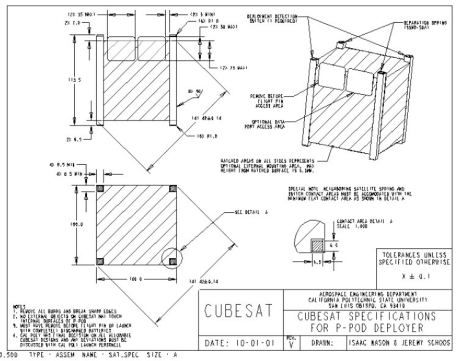
2021 NEPP Electronics Technology Workshop
17 June 2021

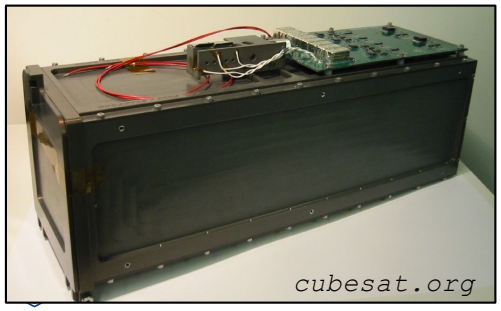
SAINT LOUIS UNIVERSITY
—
PARKS COLLEGE OF ENGINEERING,
AVIATION AND TECHNOLOGY

If You're Side-Screening This Talk

- Census Update
  - Proliferated LEO
  - Proliferated LEO
  - Proliferated LEO
- Mission assurance *(h/t Jeffrey Kelley, MSAE SLU 2021)*
  - Now with 100% more data!
  - Best practices: chicken or egg?
- A new era for Smallsats?

One-Chart Short Course: CubeSats

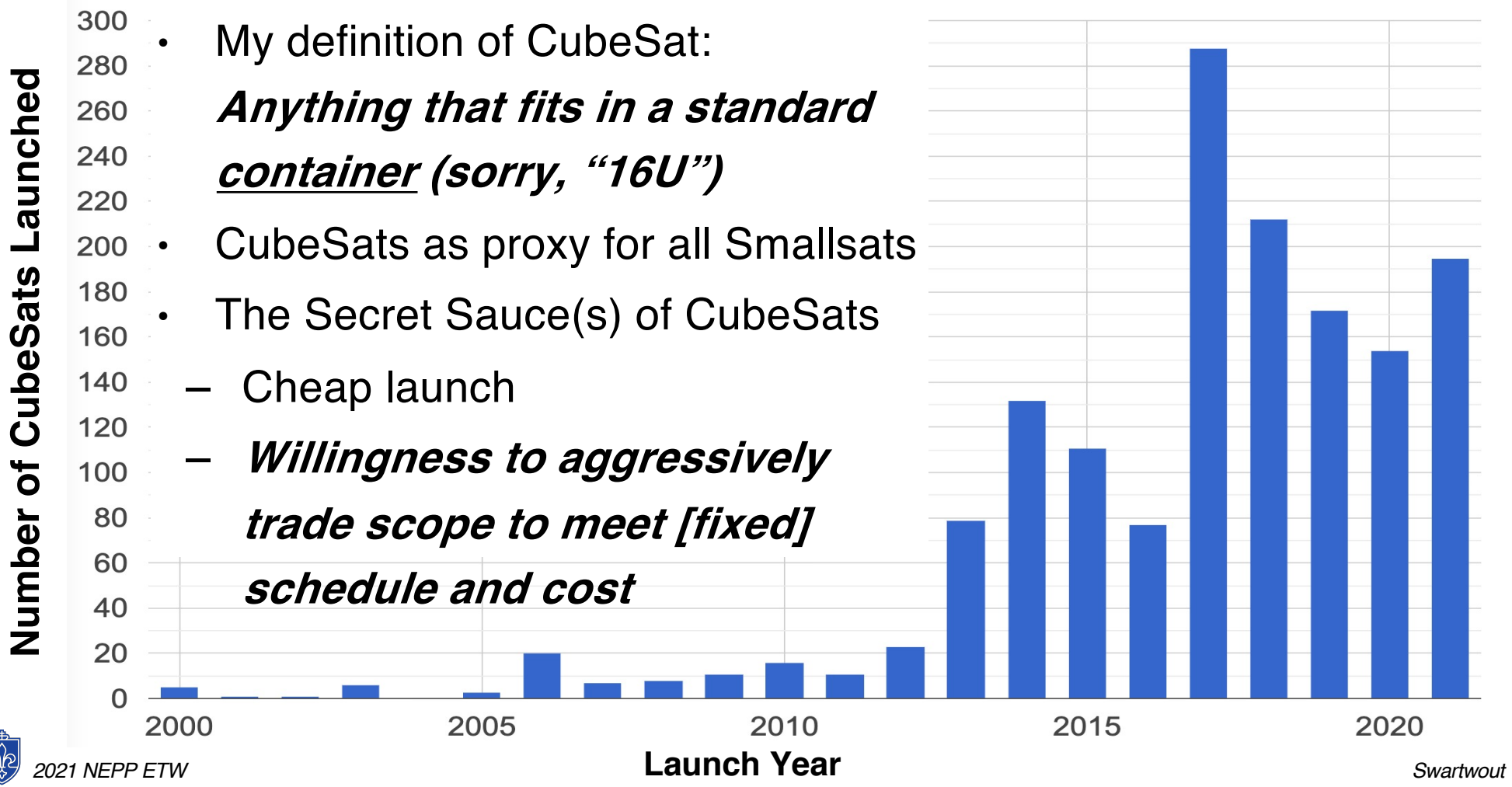




- Twiggs (Stanford) and Puig-Suari (Cal Poly) defined a standard for carrying 10 cm, 1 kg cubes into space ("1U")
- Goal: Give students easy access to spaceflight
- Unintended consequence: the P-POD makes launches cheap
- Timeline
  - **1999** Concept definition, flight validation
  - **2003** First flight with CubeSat specification
  - **2010** 70th flight
  - **2012** 100th flight; NASA selects 33 CubeSats to fly (backlog of 59)
  - **2013** 28 CubeSats on the same launch
  - **2014** ISS ejects 52 CubeSats over the course of the year
  - **2015** 400th flight
  - **2017** 600th flight, with 101 on the same launch
  - **2018** CubeSats go to Mars
  - **2021** 1500th flight, 300th builder

For Those Who Just Joined Us …

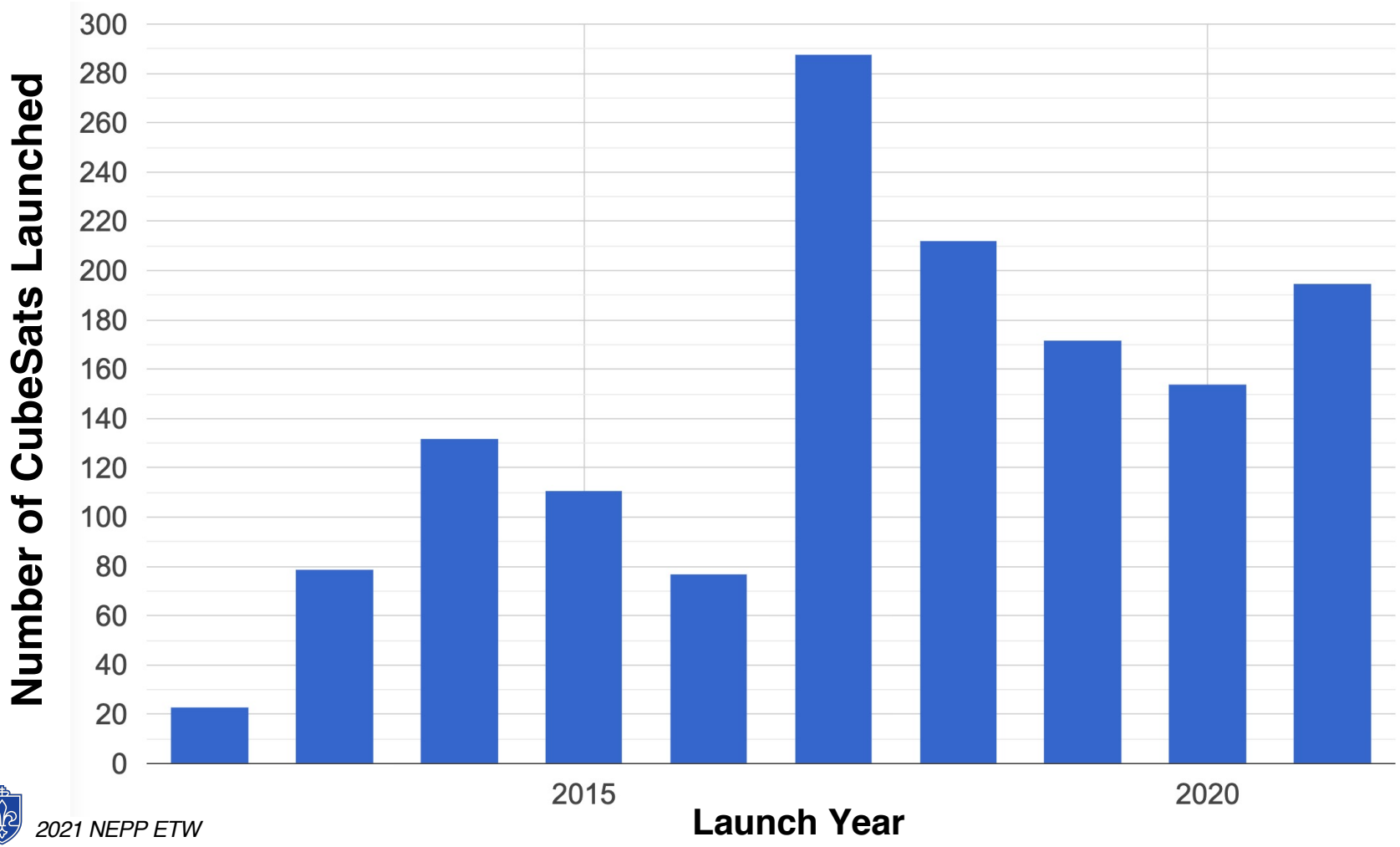
- My definition of CubeSat:
  Anything that fits in a standard container (sorry, "16U")
- CubeSats as proxy for all Smallsats
- The Secret Sauce(s) of CubeSats
  - Cheap launch
  - ***Willingness to aggressively trade scope to meet [fixed] schedule and cost***



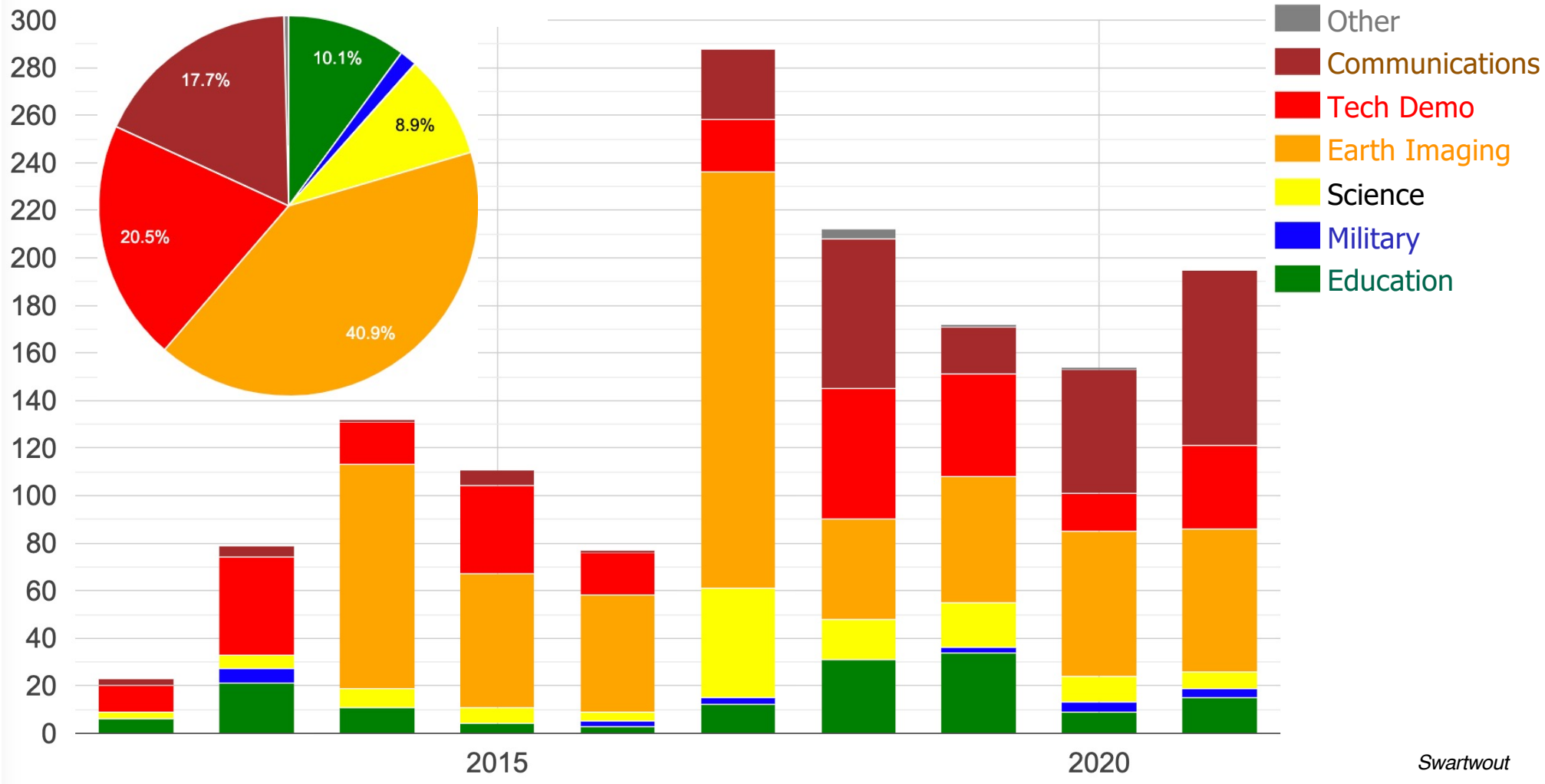
Why Fly CubeSats?

- Let's give the kids something to do
  - Nothing teaches systems engineering like … doing systems engineering
  - Let students (or new hires) burn their fingers on short, low-consequence missions
- Kick-start a space industry
  - 310 organizations from 63 nations
  - First flight in 2020: 23 organizations, 5* nations
  - First flight in 2021 (so far): 23 organizations, 3* nations
- The mission fits the form factor
  - Single-instrument science
  - Flight-testing new technologies
  - Low-rate communications (but persistent!)
  - Loose constellations (shotgun-style coverage and lots of ground processing)
  - Rapid(ish) turnaround

End of an Era *(aka 10 years is good enough)*

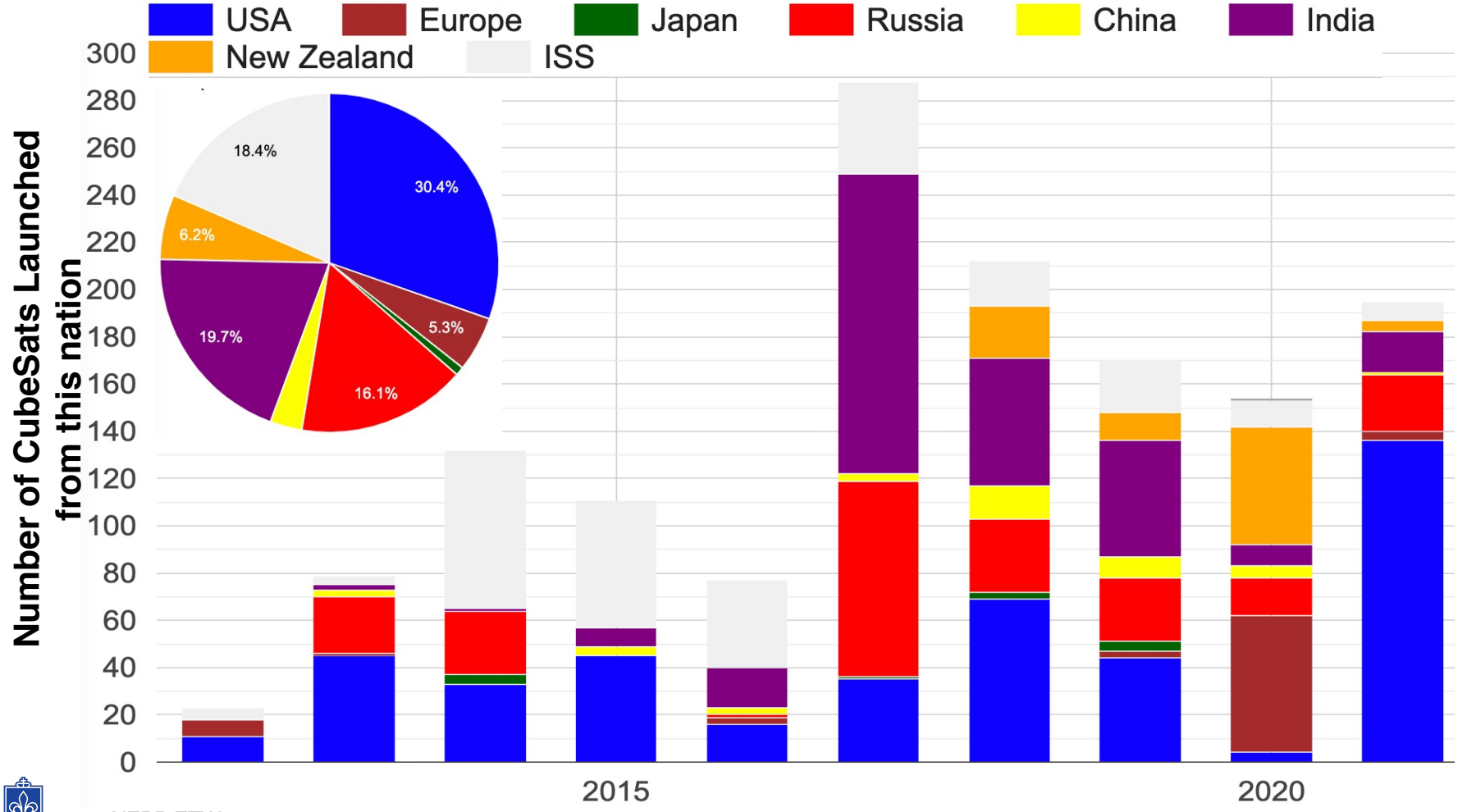


CubeSat by Mission Type (2012-2021)

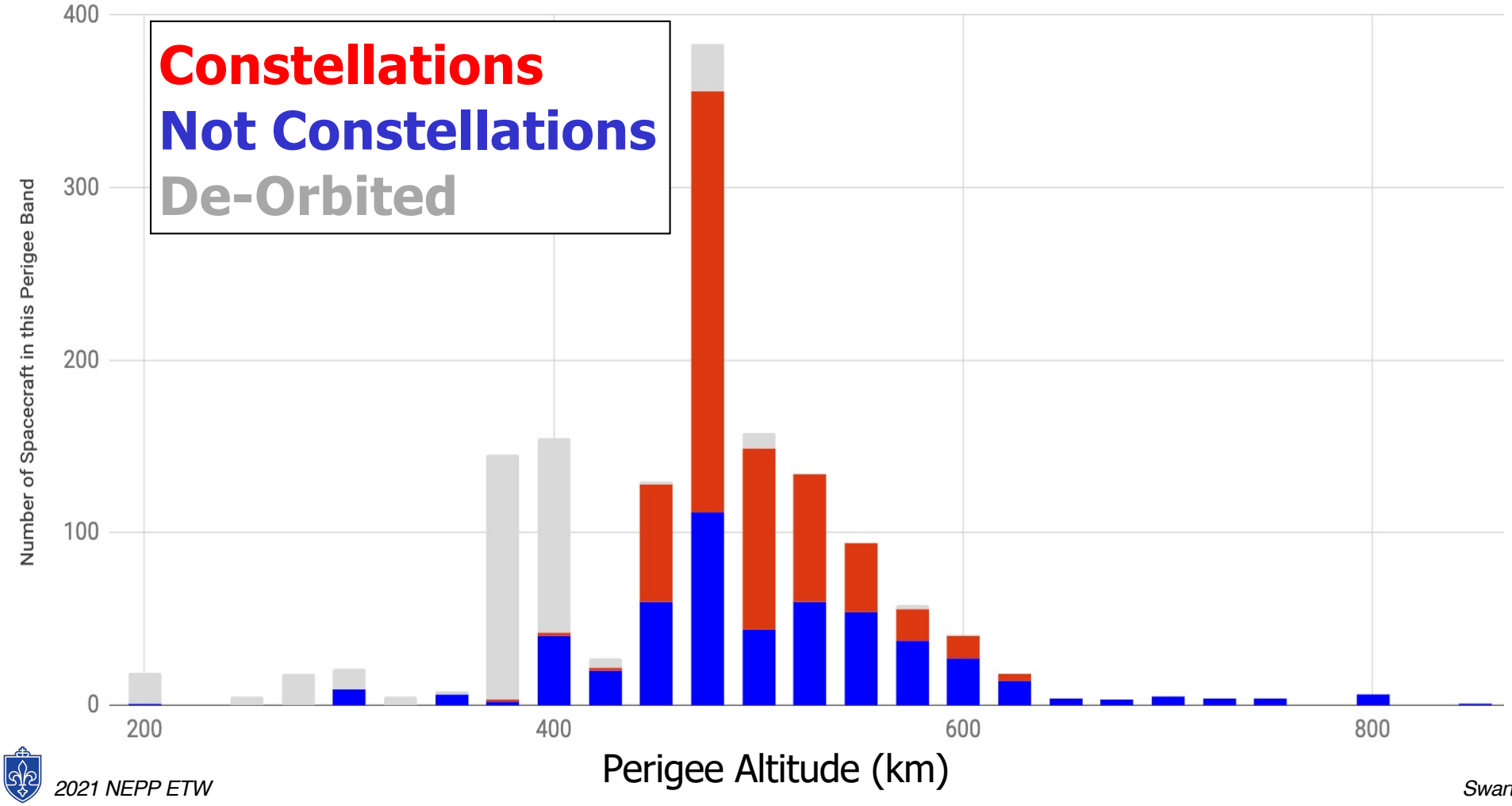


Swartwout

Worldwide Launches of CubeSats (2012-2021)



All CubeSats by Initial Orbit



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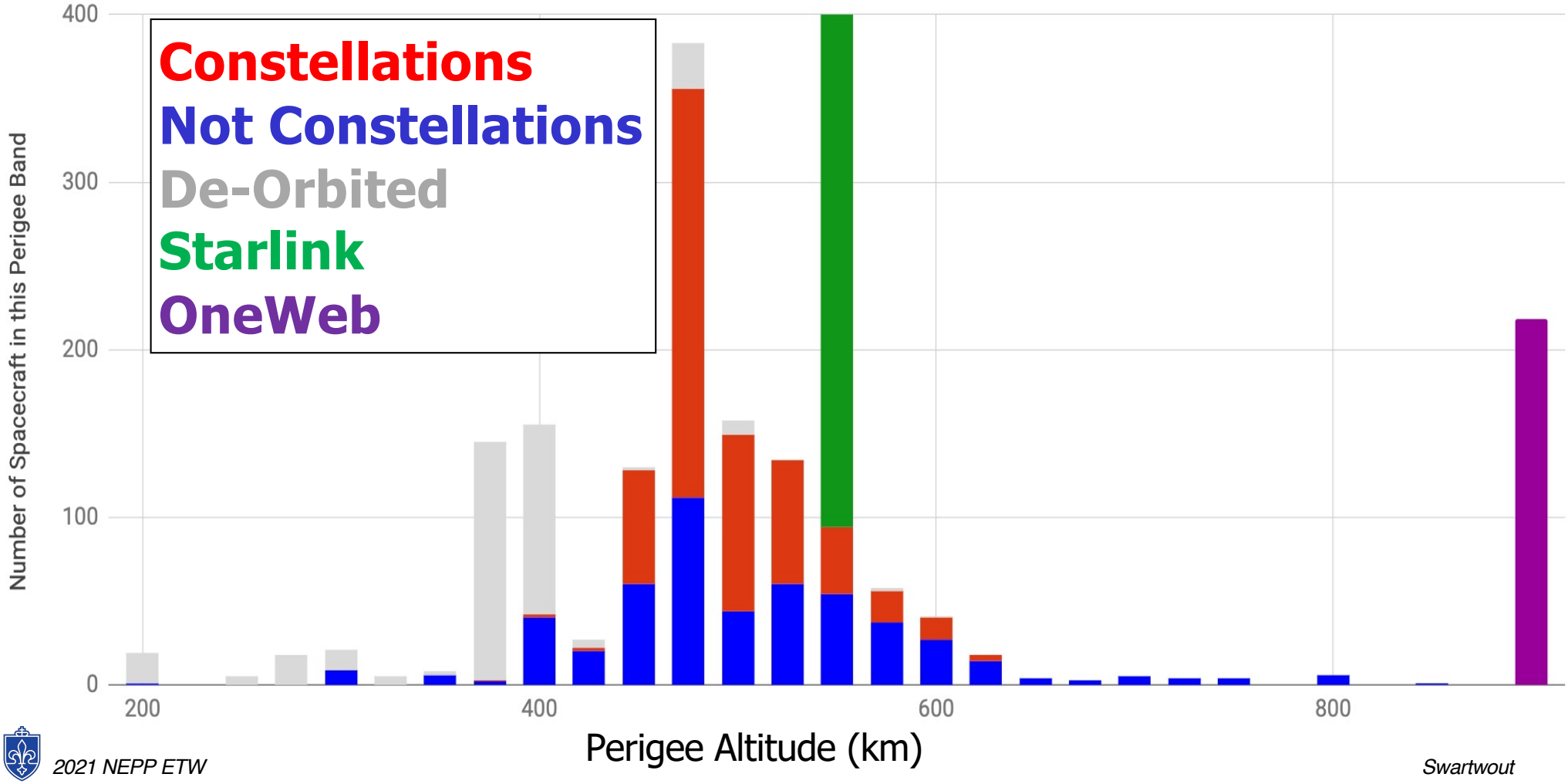

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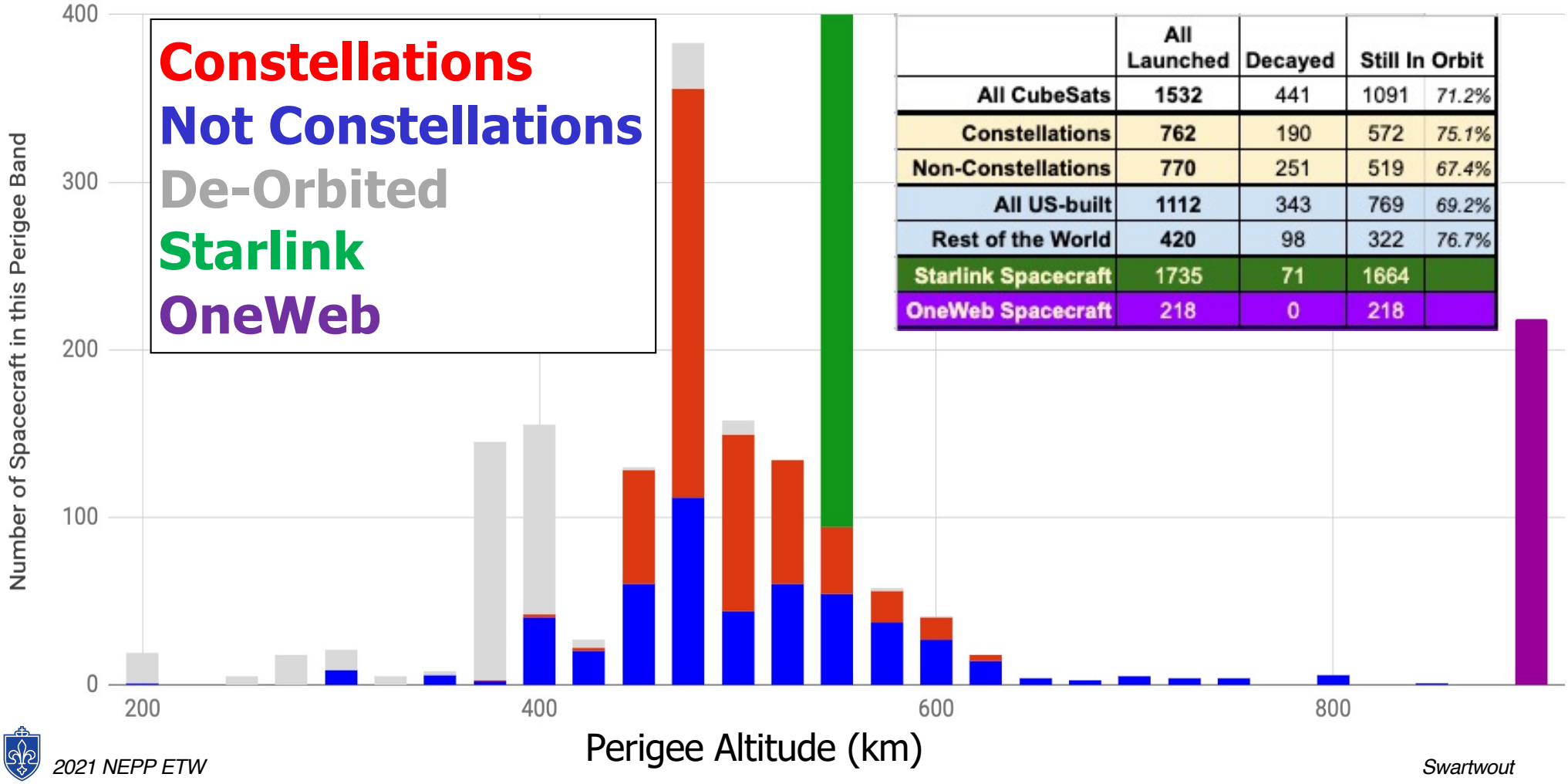

	All Launched	Decayed	Still In Orbit	
All CubeSats	1532	441	1091	*71.2%*
Constellations	762	190	572	*75.1%*
Non-Constellations	770	251	519	*67.4%*
All US-built	1112	343	769	*69.2%*
Rest of the World	420	98	322	*76.7%*
Starlink Spacecraft	1735	71	1664	
OneWeb Spacecraft	218	0	218	

2019 … things were so simple, then

Constellation	Prime Nation	Size	First Launch	Launched to Date	Launched in 2020	Launched in 2021	Mission
Planet / Skybox	USA	3U	4/19/2013	489	46	48	Whole-Earth Imaging
Spire	USA	3U	11/19/2013	143	18	10	Meteorology, AIS
Prometheus	USA	3U	11/20/2013	18	0	4	Military SIGINT+
QB50	Europe	1-3U	6/19/2014	42	2	1	Upper-atmosphere physics using global assortment of home-built spacecraft
Satellogic S.A.	Argentina	50 kg	5/30/2016	18	13	0	Earth Imaging
Cicero	USA	6U	6/23/2017	8	1	0	Radio Occultation (atmospheric physics)
Sky and Space Global	UK	3U	6/23/2017	3	0	0	Narrowband Communications
Corvus (Landmapper)	USA	6U	7/14/2017	7	1	0	Agricultural Mapping
HEAD Aerospace	PRC	50 kg	11/14/2017	5	2	0	AIS
D-Star	Germany	3U	11/28/2017	6	0	0	Communications
Swarm Technologies	USA	0.25U	1/12/2018	93	36	48	IoT Applications
ICEYE	Finland	100 kg	1/12/2018	10	2	3	Real-Time SAR
Guodian Gaoke	PRC	6U	10/29/2018	12	5	2	IoT Applications
Fleet Space	Australia	6U	11/11/2018	4	0	0	IoT Applications
Hiber	Netherlands	3U	11/29/2018	4	0	2	IoT Applications
AISTech / DANU	Spain	6U	12/3/2018	2	0	0	ADS-B constellation, IoT
Astrocast	Switzerland	3U	12/3/2018	7	0	5	IoT Applications
Magpie	PRC	6U	1/21/2019	2	0	0	Earth Imaging
Orbital Micro	USA	3U	4/17/2019	1	0	0	Microwave-based Earth observation
Hera Systems	USA	25 kg	12/11/2019	1	0	0	On-demand imaging

Bubble?

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Bubble? What Bubble?

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That This is Unreadable is Kinda the Point

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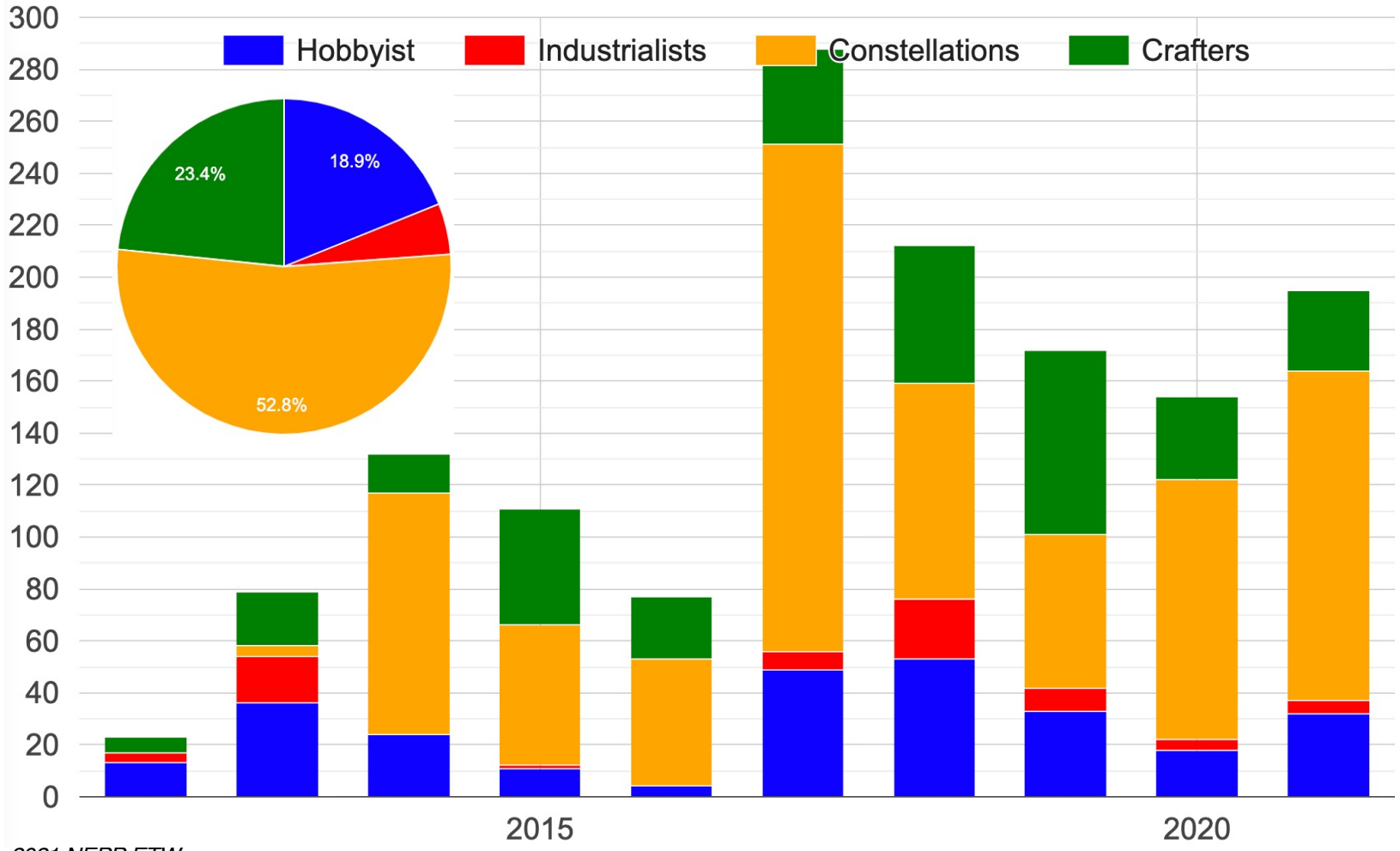
Hera Systems	USA	25 kg	12/11/2019	1	0	0	On-demand imaging
Jilin	PRC	150 kg	1/15/2020	12	12	0	Earth Imaging
Yaogan	PRC	150 kg	3/24/2020	20	7	13	SIGINT (possibly)
Xingyun	PRC	100 kg	5/12/2020	2	2	0	IoT Applications
Black Sky	USA	50 kg	8/7/2020	5	2	3	Earth Imaging
Echostar	USA	6U	8/30/2020	2	2	0	IoT Applications
Gnomes	USA	6U	8/30/2020	1	1	0	Earth/Space Weather
Capella	USA	100 kg	8/31/2020	4	1	3	X-Band SAR Imagery
GHG	Canada	15 kg	9/2/2020	2	1	1	Greenhouse Gas Monitoring
Kepler	Canada	6U	9/2/2020	13	3	10	IoT Applications
Gonets-M	Russia	300 kg	9/28/2020	6	6	0	Store-and-forward communications
KLEOS	USA	6U	11/7/2020	4	4	0	Geolocation
Unseen Labs	France	6U	11/20/2020	2	2	0	Spectrum monitoring
StriX	Japan	150 kg	12/15/2020	1	1	0	X-Band SAR Imagery
HawkEye	USA	15 kg	1/24/2021	3	0	3	Civil/Commercial SIGINT
Centauri	USA	6U	3/22/2021	1	0	1	IoT Applications
Eutelsat-ELO	Europe	6U	3/22/2021	2	0	2	IoT Applications
Myriota	Australia	3U	3/22/2021	1	0	1	IoT Applications
			Totals	**956**	**170**	**160**	

- What you can't see on this chart
  - 956 spacecraft total (!?!), including 330 in the last 18 months (!?! !?!)
  - 37 organizations put at least one spacecraft into orbit
  - At least 30 organizations are active (launched in last 18 months)
  - 10 active IoT constellations
  - 9 active Earth-imaging constellations
  - 2 military constellations
  - Don't forget the ~2000 Starlink + OneWeb birds
- "Constellation" gives the wrong impression; more like ad hoc orbits of opportunity
- Raise your hand if you knew what a SPAC was before this year
- Is there really a market for all this?

CubeSat by Developer Class



None of These Things are Quite Like the Others …

- **Hobbyist**
  - No real experience in the field
  - Building for fun & future profit
  - **Ad hoc practices**
  - **NEW: < 4 missions**

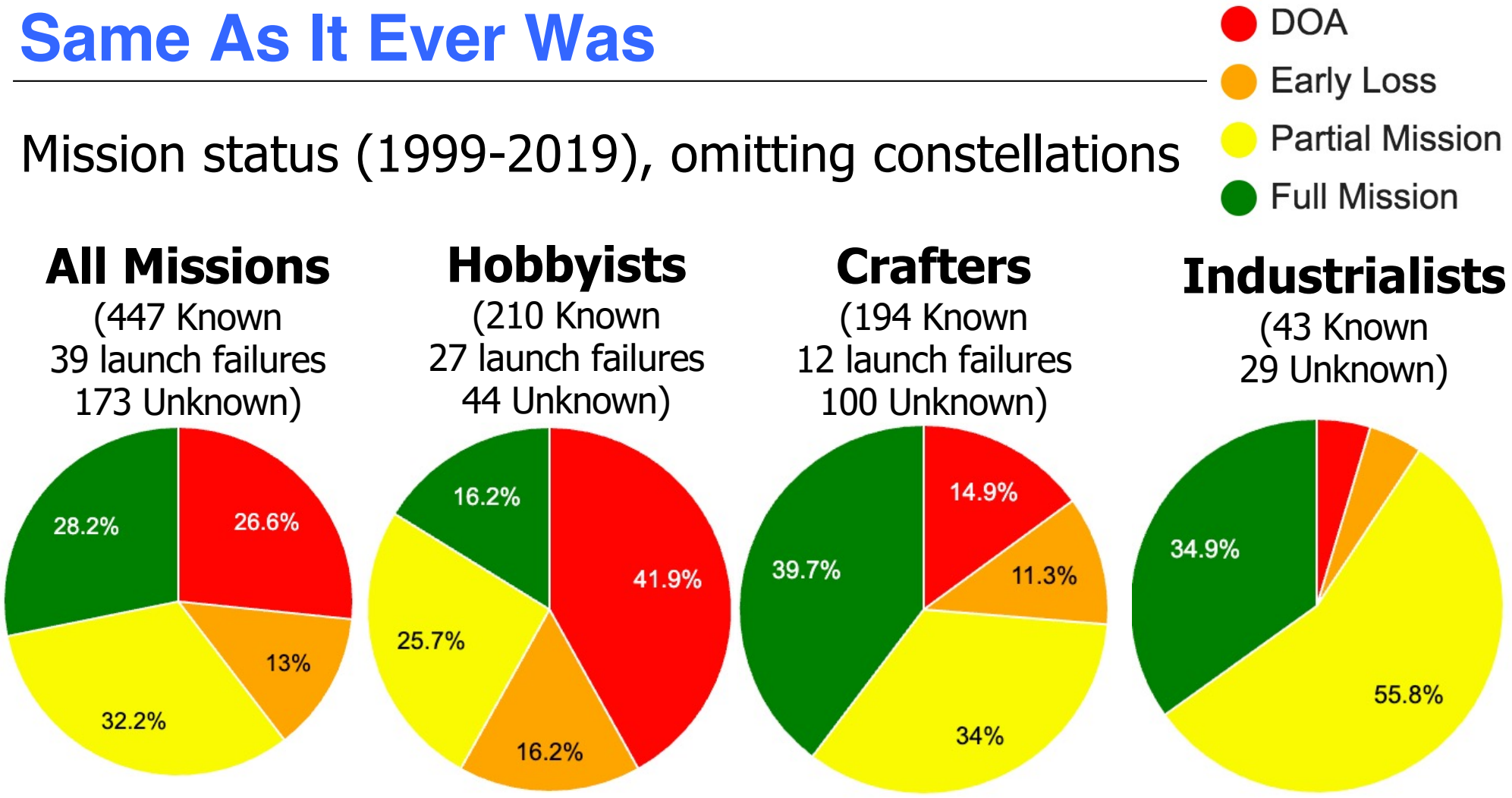
- **Industrialist**
  - Experienced builders of big spacecraft
  - Building under gov't contract
  - **Standard space system practices, with some truncation**
  - **Smallsats are not the main business line**

- **Crafter**
  - Experienced builders of small spacecraft
  - Working under contract
  - **Streamlined practices, experientially developed**
  - **NEW: 4+ missions, smallsats are main business line**

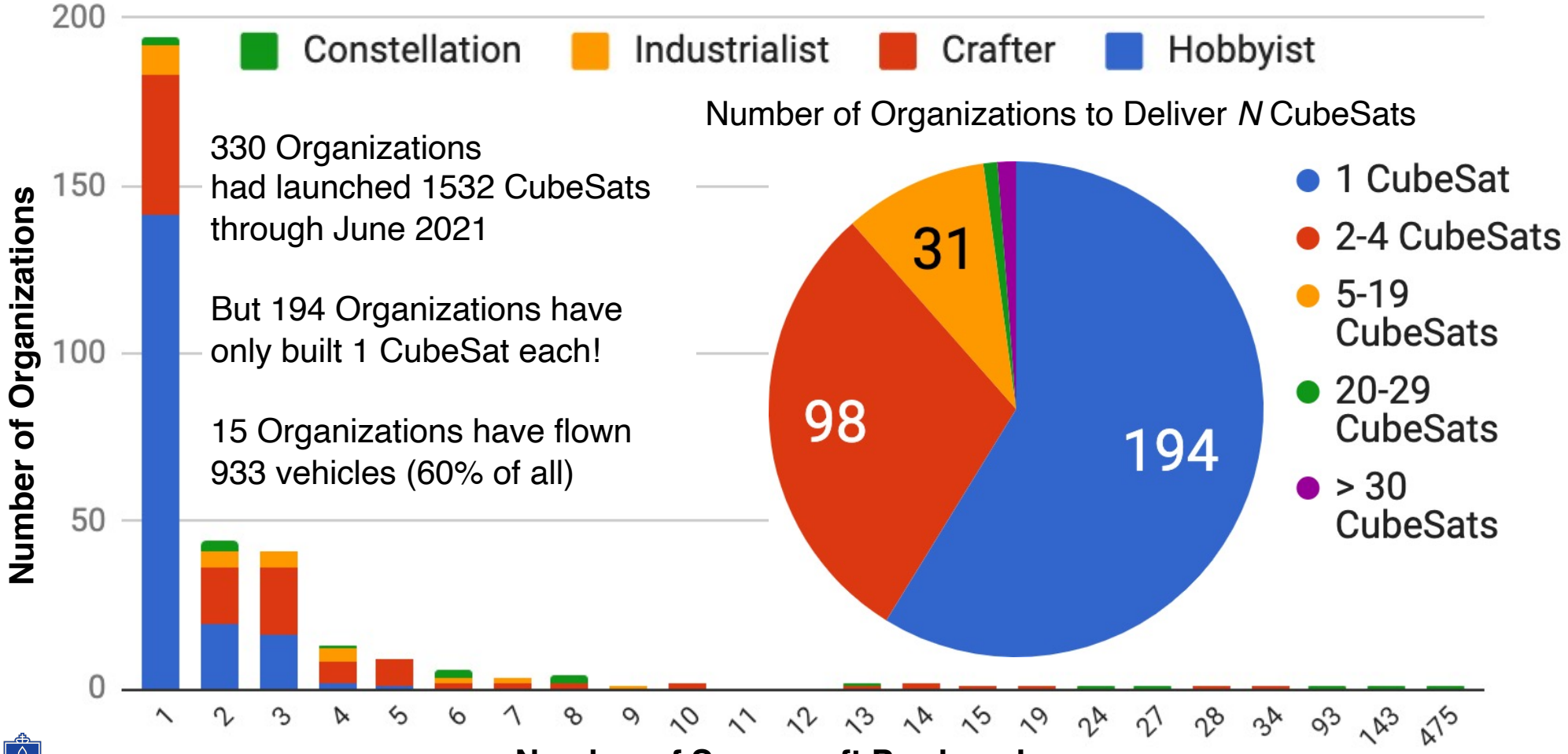
- **(Smallsat) Constellations**
  - Providing a geographically-distributed service (imaging, comm)
  - **Mission can be met with an ad hoc (?!?) implementation of orbits**
  - Spacecraft/launch costs are effectively free (I did say "*effectively*")

Same As It Ever Was

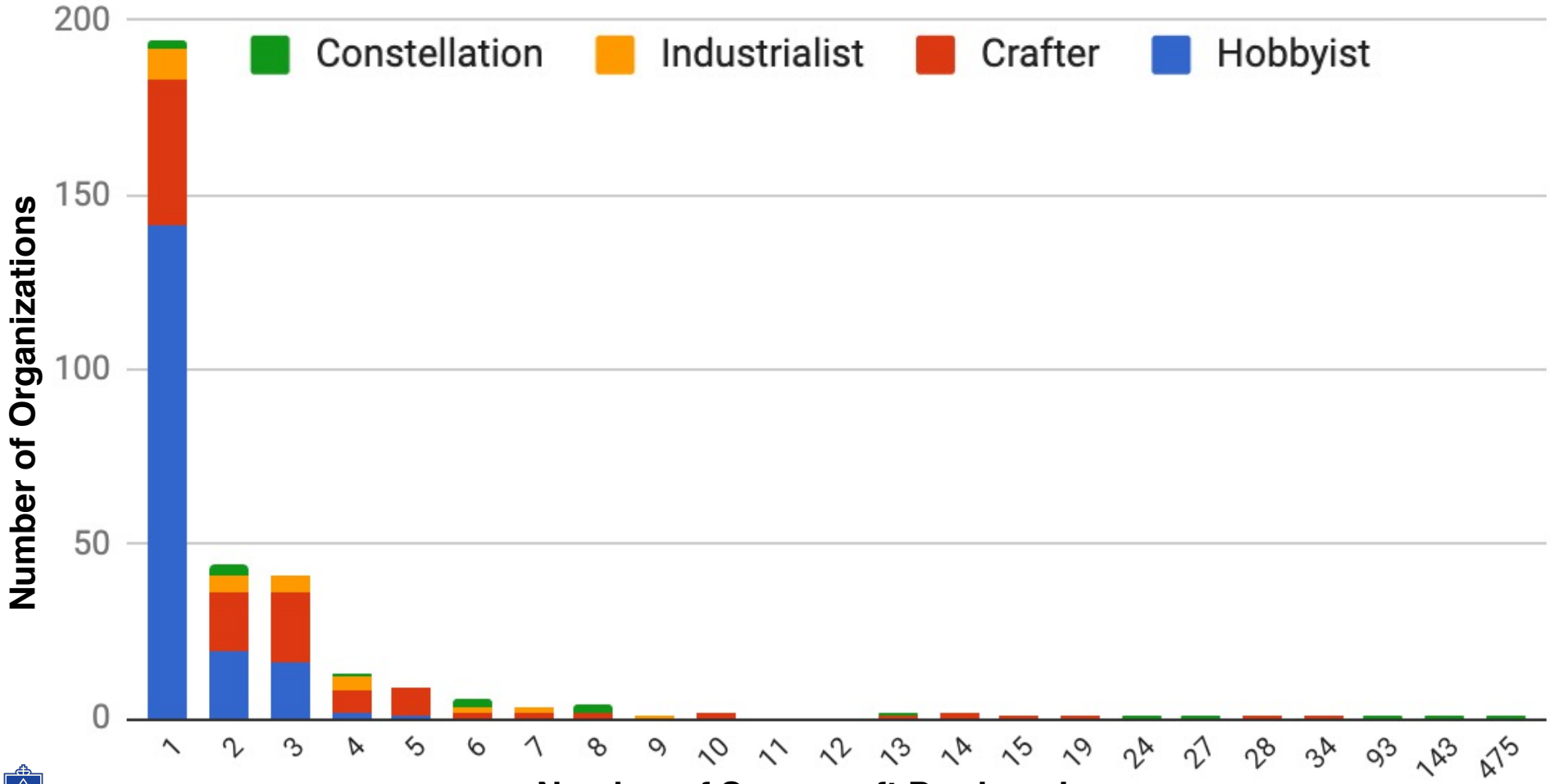
Mission status (1999-2019), omitting constellations



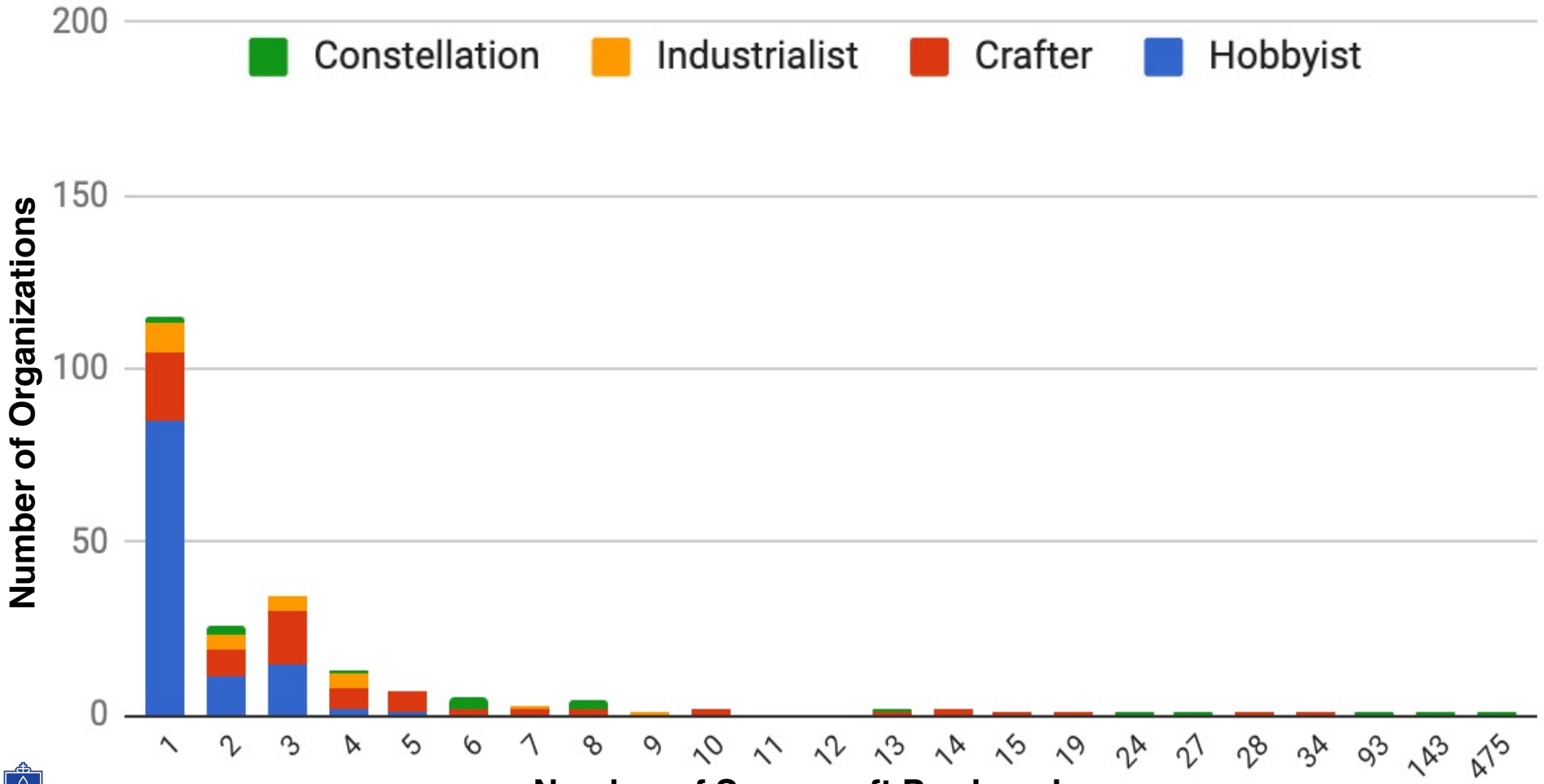
Hobbyists: It's Hard to Improve, When You Don't Repeat!



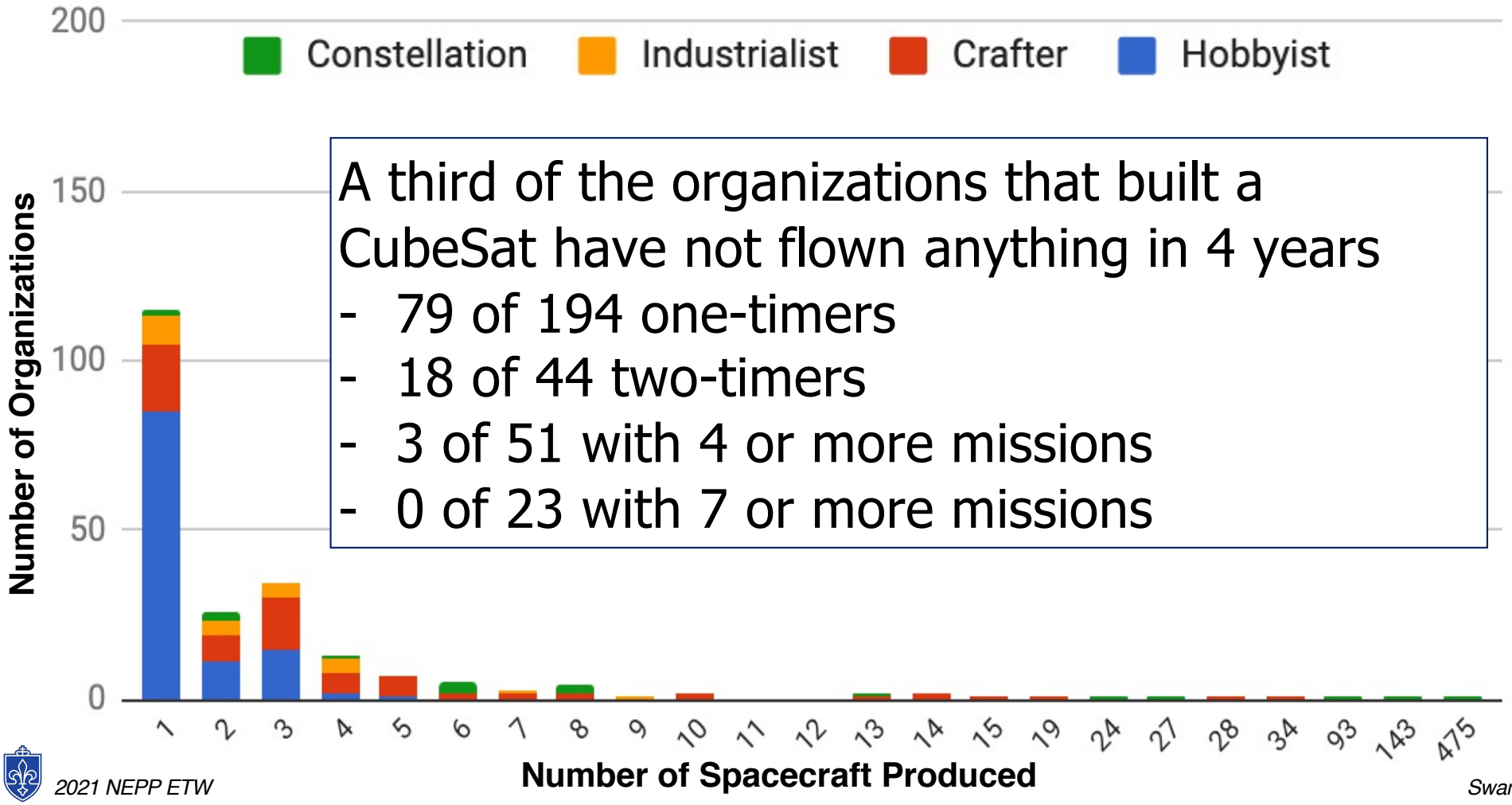
Count of Organizations with at least one mission through June 2021



Organizations with at least one mission between June 2017 – June 2021



Organizations with at least one mission, June 2017 – June 2021



A third of the organizations that built a CubeSat have not flown anything in 4 years

- 79 of 194 one-timers
- 18 of 44 two-timers
- 3 of 51 with 4 or more missions
- 0 of 23 with 7 or more missions

Better Research Through Zoom?!?!

- Source: J. Kelley, *Examining the Influence of Developer Background on CubeSat Environmental Testing*, SLU MS Thesis, May 2021
- Interviews with 14 CubeSat Developers
  - **Hobbyist**: ASU, UMN, USI, NNU, SLU
  - **Crafter**: Cal Poly, Montana St., USNA, Space Dynamics Lab, NanoAvionics
  - **Industrialist**: LASP, Goddard, JPL, APL
- Focus area: Testing (vibration, “thermal”)
  - What are the success criteria for this test?
  - Would you fly without performing this test?

I'm Not Trying To Torture Your Eyes… (okay, maybe a little)

Test Type	Vibration Testing						Vibe Analysis	Thermal Vacuum								Thermal Analysis	Ambient Pressure Thermal Testing
Targeted Failure Mode(s)	*Fasteners coming loose*	*Components cracking and/or chipping*	*Internal fasteners, parts, or connectors coming loose*	*Hard-to-see mechanical failure or yielding*	*Unspecified mechanical failure affects operation of the electronics*	*Mechanical anomaly prevents proper deployable deployment*	*Structural surprise consumes schedule*	*Component thermally stressed beyond spec to the point of failure*	*Incorrect thermal analysis leads to flawed hardware or test design, allowing latent problems*	*Thermal runaway leads to overheating /overcooling*	*Unspecified mechanical failure that permanently affects electronics*	*Thermal mismatch or similar phenomenon causes deployable failure*	*Electronic malfunction due to temperature prevents spacecraft from activating*	*One-time thermal stress causes hardware to break*	*[several]*	*Spacecraft system is inherently thermally doomed*	*[see Table 2]*
Success Criterion	*Visual Inspection of fastener position*	*Visual inspection of spacecraft exterior*	*No rattling heard when spacecraft is rolled*	*Pre/post sine sweeps compared*	*Post-vibe software functional testing*	*Post-vibe deployable testing*	*FEM indicates survival of "design-to" levels*	*Component temperature values stay within safe limits*	*Thermal model validated through thermal balance*	*Real-time temperature trends don't diverge*	*Spacecraft behaves same in pre/post functional tests*	*Deployables fire successfully at thermal extreme*	*Spacecraft starts successfully at hot & cold operating temperatures*	*Spacecraft operates after hot/cold survival temperature exposure*	*Spacecraft operates nominally over all states in TVAC cycling*	*Thermal model indicates spacecraft functionality*	*Components function over their entire specified temperature range*
H	no	yes	yes	no	yes	no	yes	no thermal test	no thermal test	no thermal test	no thermal test	no thermal test	n/a (no thermal testing)	n/a (no thermal testing)	n/a (no thermal testing)	yes	n/a (no thermal testing)
	no	yes	no	no	yes	no	no	no thermal test	no thermal test	no thermal test	no thermal test	no thermal test	n/a (no thermal testing)	n/a (no thermal testing)	n/a (no thermal testing)	yes	n/a (no thermal testing)
	no	yes	yes	no	yes	n/a	no	no	no	no	yes	n/a	yes	no	no	no	no
	no	no	yes	yes	no	no	yes	no	no	no	barely	no	no	no	no	no	no
	no	yes	no	no	yes	no	no	no thermal test	no thermal test	no thermal test	no thermal test	no thermal test	n/a (no thermal testing)	n/a (no thermal testing)	n/a (no thermal testing)	no	n/a (no thermal testing)
C	yes	yes	yes	yes	yes	no	no	yes	yes (ambient, calcs)	yes	real time	yes	yes	no	yes(2 cycles)	spreadsheets	yes (system-level in TVAC & amb.)
	yes	yes	yes	yes	yes	yes	yes	yes	effectively		real time	yes (cold)	yes	yes (cold for sure)	yes (3-4 cycles)	yes	yes, subsys. level at amb. pressure
	yes	yes	yes	yes	yes	no	no	no	no	no	yes	no	no	no	no	hand calculations	no
	yes	yes	yes	yes	yes	sometimes	no	yes	no	yes	real time	yes	yes	likely (hot)	yes; 2-3 cycles	yes	may cycle sys. at amb.(after TVAC)
	effectively	yes		yes	yes	effectively		yes	no		sort of	yes	yes, both	yes (both)	yes (4-5)	no	
I	effectively	yes	yes	yes	yes	yes	yes	yes	yes		yes	yes (cold)	yes	yes (cold)	yes (4-8)	yes	Use TVAC instead
	yes	yes		yes	yes	yes	yes	yes	only for payload		yes	yes	yes	yes	yes (3 cycles)	yes	Use TVAC instead
		yes		yes	yes			yes for payload				likely				hand calcs for payload	
	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	real time	yes (cold)	yes	yes (both)	yes (7 cycles)	yes	Use TVAC instead

Our Guesses Were Half-Right, and Now We Don't Know the Half of It

- Hobbyists: Doomed from the start
  - Belief that "Do No Harm" = "My Mission Will Work"
  - "We didn't realize that _____ would take so much time!"
  - **What is magical about 4 missions?** (Cause or effect?)
- **What tests do Crafters run?** Whatever the customer requires!
- Crafter vs Industrialist: Differences of degree and design heurestics
  - Healthy fear of hard-to-test items (deployables)
  - Hypothesis: a the (?) differentiating factor is the ability/willingness to **aggressively** trade performance vs cost/schedule
  - *Can't be ruled out, yet: these were all Crafters*

[Insert shameless plug for SEE/MAPLD (30 August)]

I'm Still Stuck on that "Proliferated LEO" Thing

- My well-informed but admittedly subjective history of small satellites
  - 1960 (*Dark Ages*): **Everything is a Smallsat**, and there was a lot more freewheeling design than you know
  - 1970 (*Stone Age*): **Smallsats as mission risk**
  - 1981 (*pre-Industrial Revolution*): **Smallsats as niche market**
  - 2002 (*Original Recipe Silicon Valley*): **Smallsats as university toy** (more niche, more risk)
  - 2009 (*Cambrian Explosion*): **Smallsats as legitimate platform**
  - 2020 (*The Internet Ruins Everything*): **Smallsats as meme stock**?
- Has the marketplace already addressed the mission assurance question?
  (Tyvak, Blue Canyon, GOMSpace, NanoAvionics, Planet, Spire, Starlink, OneWeb …)
- Things to worry about
  - Regulators gonna regulate, and a most rational response is to regulate universities out of the CubeSat business
  - I've been saying "Bubble" for 4 years, so feel free to ignore this, but, still: **Bubble?**

Acknowledgements

- Data Sources
  - Public: Gunter's Space Page (international launch log)
  - Public: Jonathan's Space Report (orbital elements)
  - Public: DK3WN Satblog (university/amateur operations)
  - Public: Union of Concerned Scientists (operational status)
  - Public: Program websites, conference presentations
  - Public: Bryan Klofas (communications/operational status)
  - Public: SatNOGS (operational status)
  - Private: Personal communications
- NASA NEPP (80NSSC20K1230)
  - Jeffrey Kelley (MSAE 2021)
- Student research team: Daniel Angkiat, Caleb Burlison, Samantha Carlowicz, Scott Elliott, Connor Highlander, Andie Kaess, Tinevimbo Ndlovu, Cody Powers, Patrick Sullivan, Celia Taylor-Puckett, Adam Walker, Sean Walsh

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2021 NEPP Electronics Technology Workshop
17 June 2021

SAINT LOUIS UNIVERSITY
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