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SPACE STUDIES BOARD

Achieving Science with CubeSats: Thinking Inside the Box

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Key Elements of Charge to Committee

- Develop a **summary of status**, capability, availability, and accomplishments in the government, academic, and industrial sectors

- Recommend **potential near-term investments** that could be made to improve the capabilities and usefulness of CubeSats for scientific return and to enable the science communities' use of CubeSats

- Identify a set of **sample priority science goals** that describe near-term science opportunities

The Report: goo.gl/osCSQ3 (free)

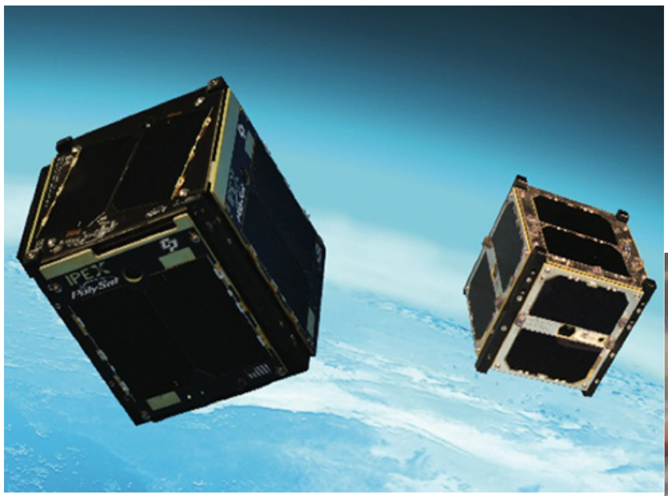
1. Introduction
2. CubeSats as disruptive innovation
3. CubeSats for education and training
4. Science: Impact and potential
    1. Solar and space physics
    2. Earth science and applications
    3. Planetary science
    4. Astronomy and astrophysics
    5. Biological and physical sciences in space
5. Technology development
6. Policy: Challenges and solutions
7. Conclusions and Recommendations

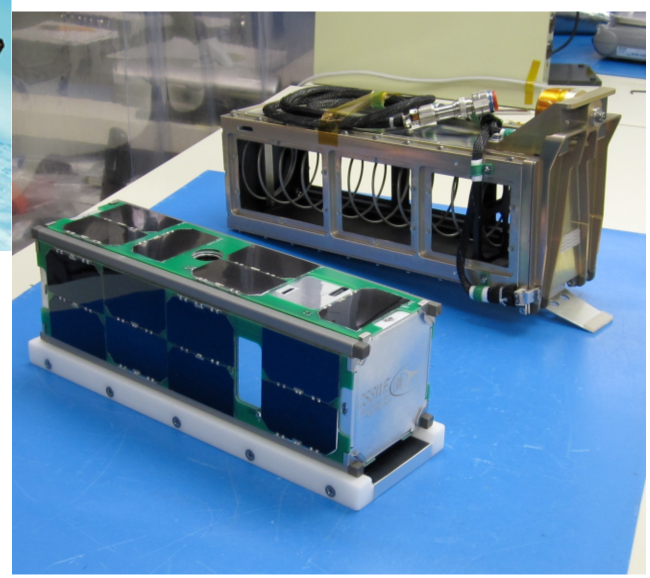
Overview

1. Based on detailed analysis of available data
2. Recognized similarity to disruptive innovation
3. Analysis of science publications: CubeSats can do high priority science
4. Science potential in all science divisions to varying degrees. However, not every application is appropriate for CubeSats.
5. Potential is realized if a number of conditions are fulfilled
    1. Technology and connections to industry
    2. Policy issues
    3. Programmatic and management issues

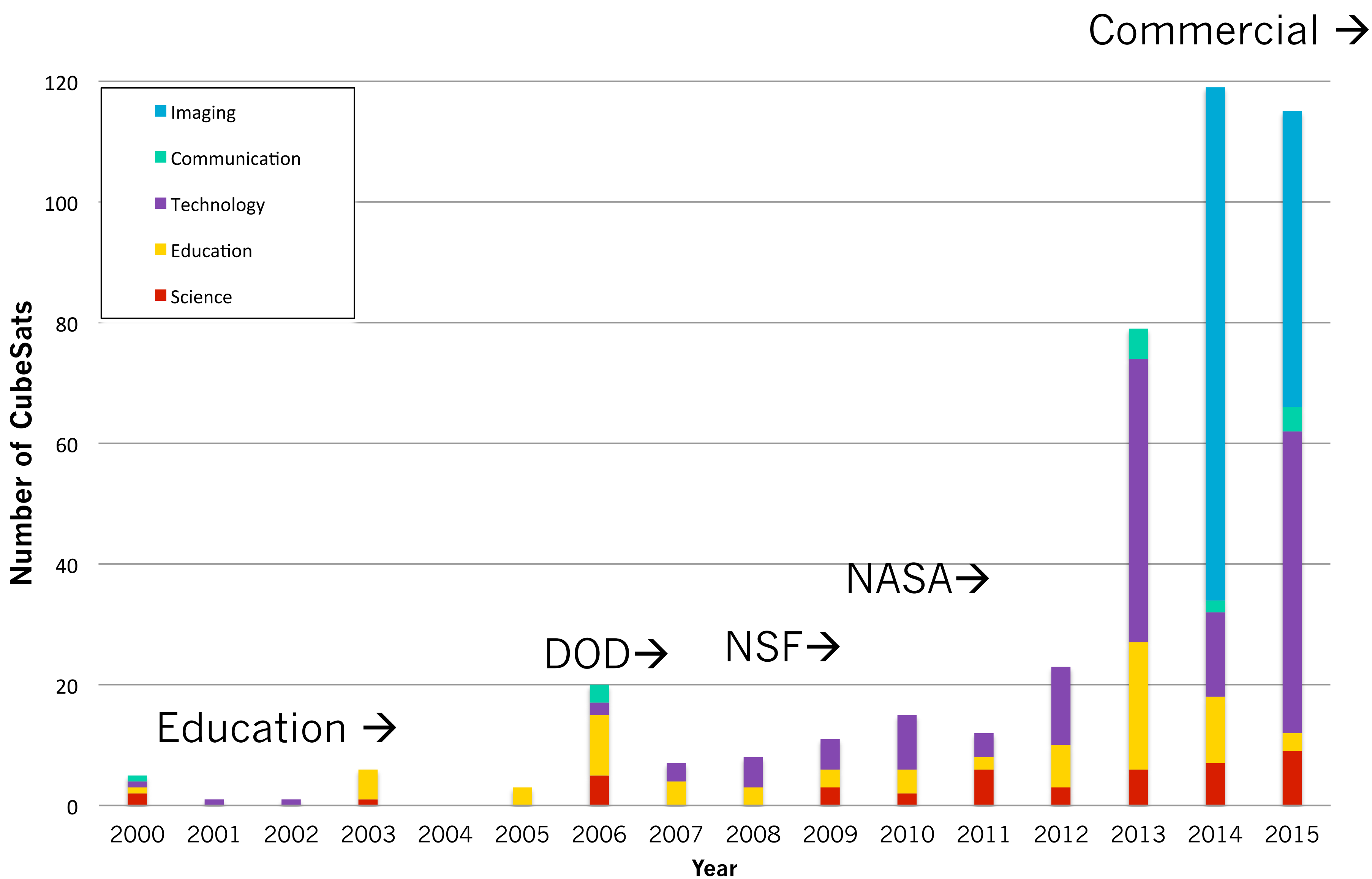
What is a CubeSat?

For the purpose of this study the committee defines a CubeSat as a spacecraft sized in units, or U’s, typically up to 12 U that is launched fully enclosed in a container

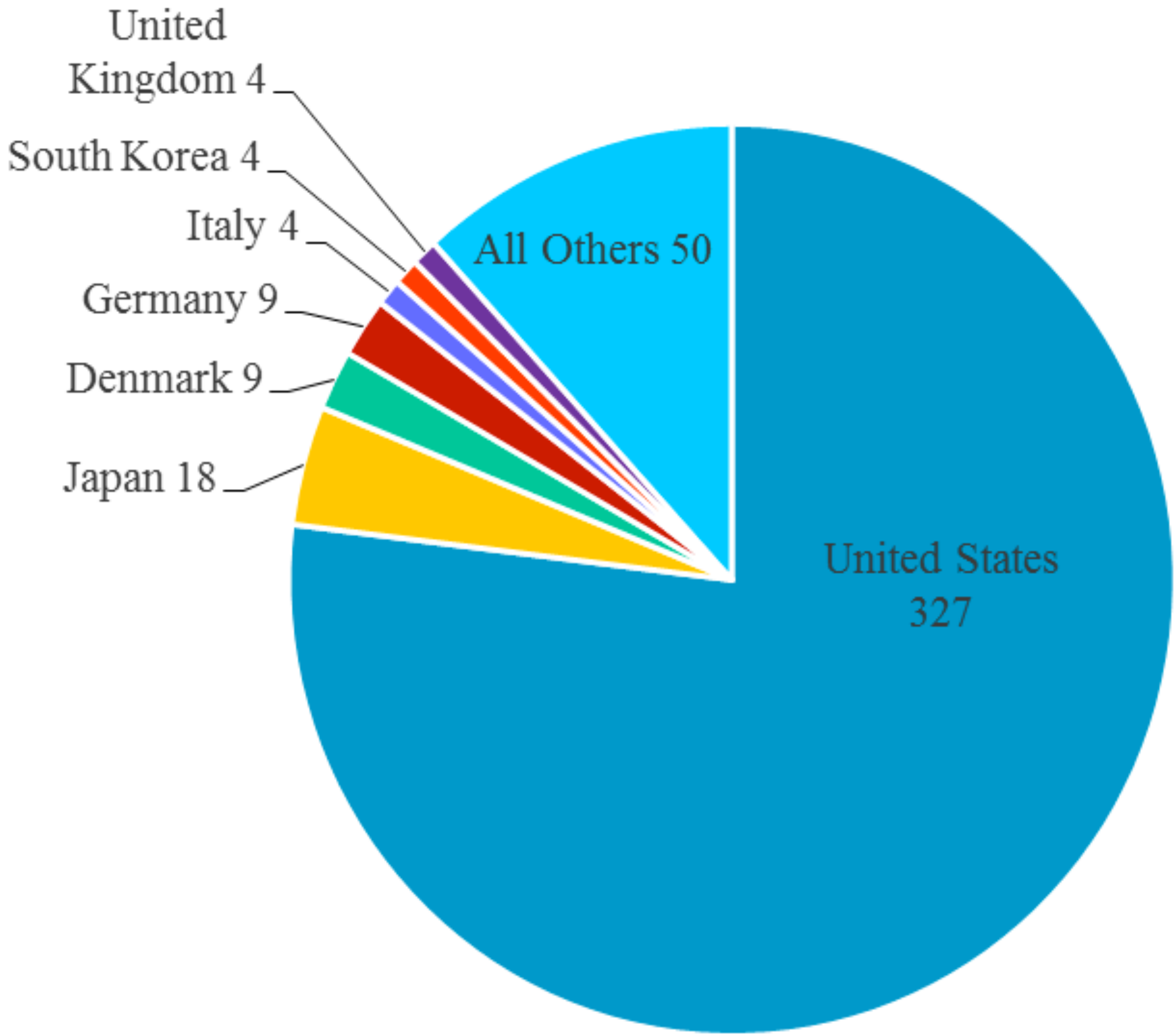




US CubeSats Launched – by Mission Type

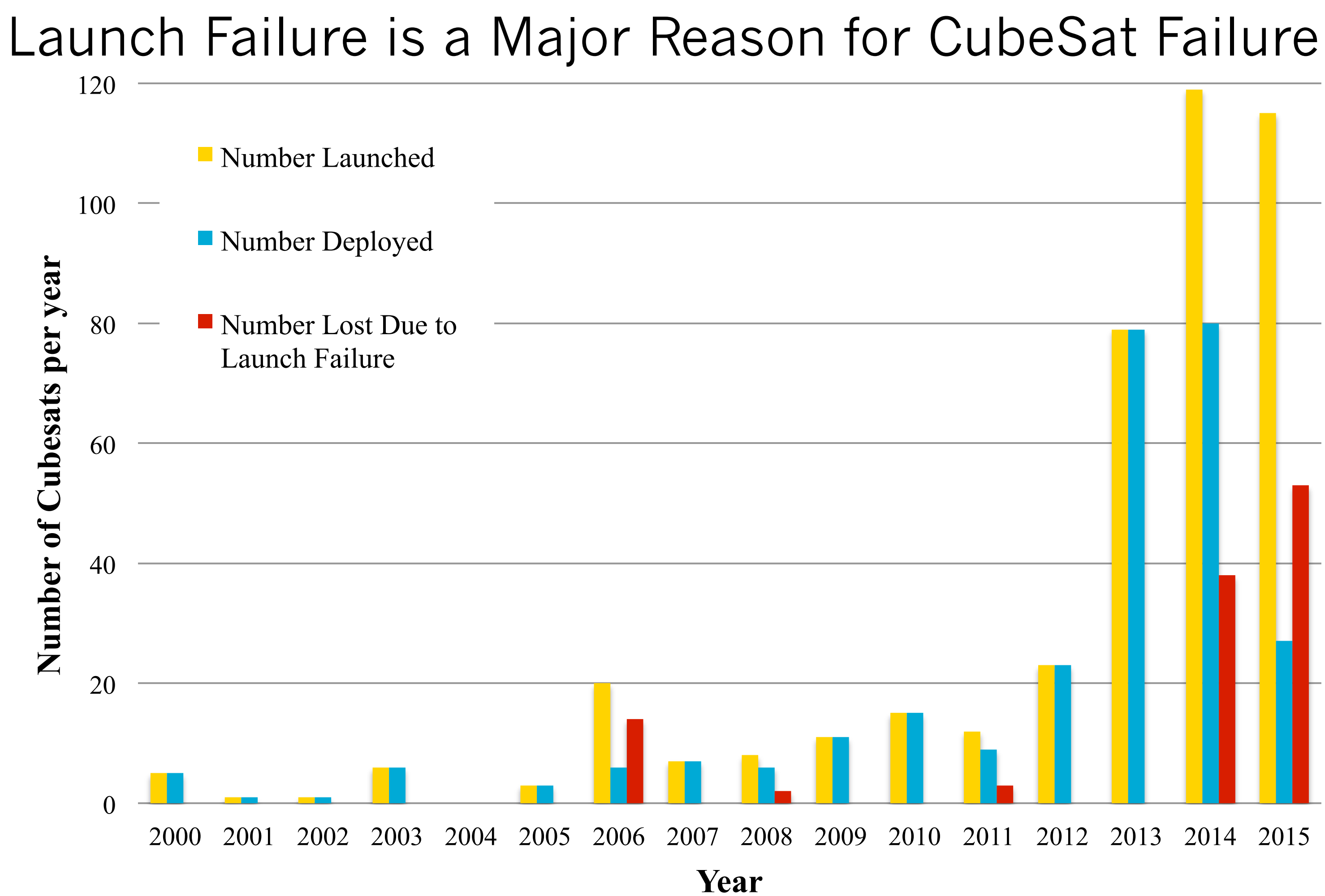


International Participation



Funding Program	CubeSat Missions Launched	CubeSat Missions Planned	Launch Years
NASA			
Heliophysics	MinXSS	CeREs, CuSP, ELFIN-STAR,[a] HeDI, SORTIE, TBEx	2015-2018
Earth Science	GRIFEX, IPEX, MCubed/COVE (2)	CIRAS, CIRiS, CubeRRT, HARP, IceCube, LMPC, MiRaTA, RainCube, RAVAN, TEMPEST-D	2011-2018
Planetary Science	O/OREOS	INSPIRE (2), LunaH-Map, MarCO (2), Q-PACE Technology Development Only: DAVID, HALO, MMO	2010-2018
Astrophysics		HaloSat	2018
Advanced Exploration Systems and Human Exploration and Operations	GeneSat, PharmaSat, SporeSat (2)	BioSentinel, EcAMSat, Lunar Flashlight, Lunar IceCube, NEA Scout, Skyfire	2006-2018
Space Technology	EDSN (8),[b] NODeS (2), OCSD-1, PhoneSat (5)	CPOD (2), CSUNSat-1, ISARA, iSAT, OCSD (2)	2013-2017
Centers (Internal)			2008-2018
Ames Research Center	PreSat,[c] TechEdSat (3)	KickSat, TechEdSat-5	
Ames Research Center and Marshall Space Flight Center	NanoSail-D (2)		
Goddard Space Flight Center		CANYVAL-X, Dellingr, ESCAPE, RBLE	
Jet Propulsion Laboratory	LMRST, RACE[d]	ASTERIA, MITEE	
Kennedy Space Center		Cryocube, StangSat	
NASA IV&V Facility		STF-1	
National Science Foundation	CADRE, CSSWE, CINEMA-1, DICE (2), ExoCube, FIREBIRD (4), Firefly, RAX (2)	ELFIN [a], ISX, IT-SPINS, LAICE, OPAL, QBUS/QB50 (4), TRYAD (2)	2010-2018

CubeSat Success Rate



- Education focused missions have different success metrics
- 33% of CubeSats deployed have fulfilled mission goals; 34% partially fulfilled goals: 67% total "success" rate.
- 2000-2007: 35% successful; 2008-2015: 71% successful (getting better)
- NSF CubeSats, including re-flight: 92% successful (Fly-learn-refly helps)

Concept of a Disruptive Innovation

- "Process by which a product or service takes root initially in simple applications at the bottom of a market and then relentlessly moves up market [...]."
  Clayton Christenson, 1995
- Has been used to describe many shifts in the economy
  - Personal computers (that disrupted the mainframe computer industry)
  - Cellular phones (that disrupted fixed line telephony)
  - Smartphones (that continue disruption of multiple sectors, computers, digital cameras, telephones, and GPS receivers)
- End-state and especially level of disruption is unclear at beginning

CubeSats Share Characteristics of Disruptive Innovations

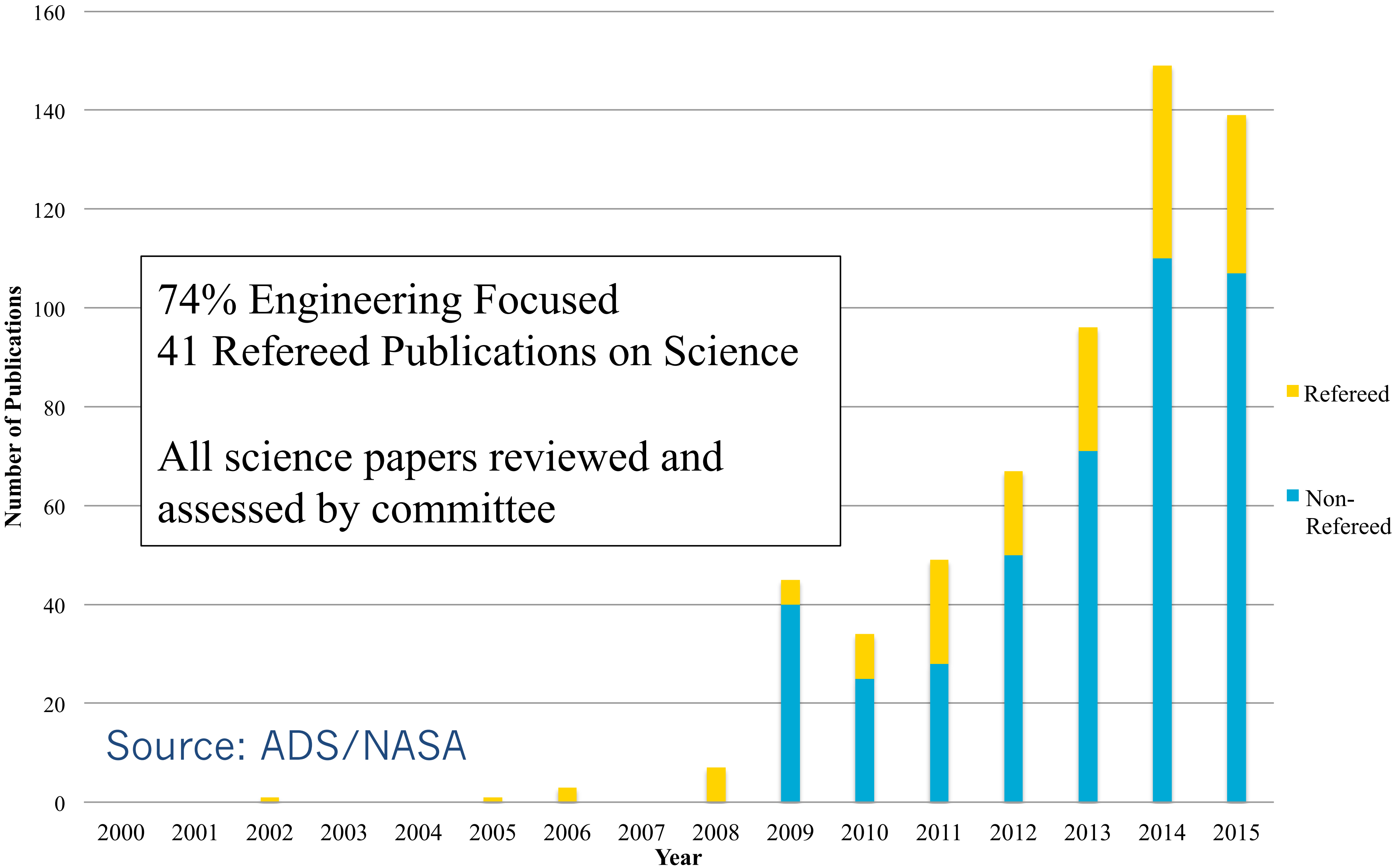
- **Performance**. Early CubeSats were essentially “beepsats”
- **Cost.** Hardware for a basic CubeSat can be purchased for a few tens of thousands of dollars
- **Users**. CubeSats are introducing students and other participants to space technology; introducing the potential for new functionalities such as stop-and-stare and multi-hundred/thousand swarm systems
- **Speed**. CubeSats began as platforms for technology testing, and are being considered for advanced missions such providing real-time relay communication
- **Origin.** Introduced by educators not the stalwarts of aerospace
- **Enabling technology.** Propelled by advances in software, processing power, data storage, camera technology, compression and solar array efficiency
- **Development models**. Adopted by entrepreneurs using fly-test-refly and other lean manufacturing technology and business models

End-state and especially level of disruption CubeSats may create is unclear

What CubeSats Can Enable

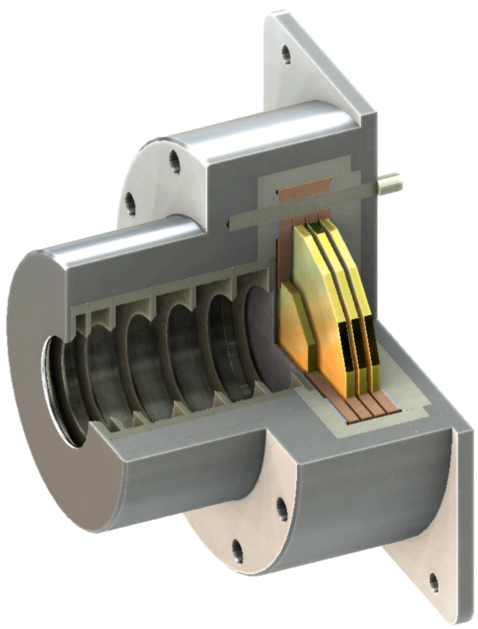
- They are standardized – creation of supply chain
- They are cheaper - conduct of higher risk activities, “fly-learn-refly” paradigm
- Enables new mission types, especially high-risk orbits and secondary lines of sights, as well as targeted science
- Enables creation of entirely new architectures, especially constellations and swarms

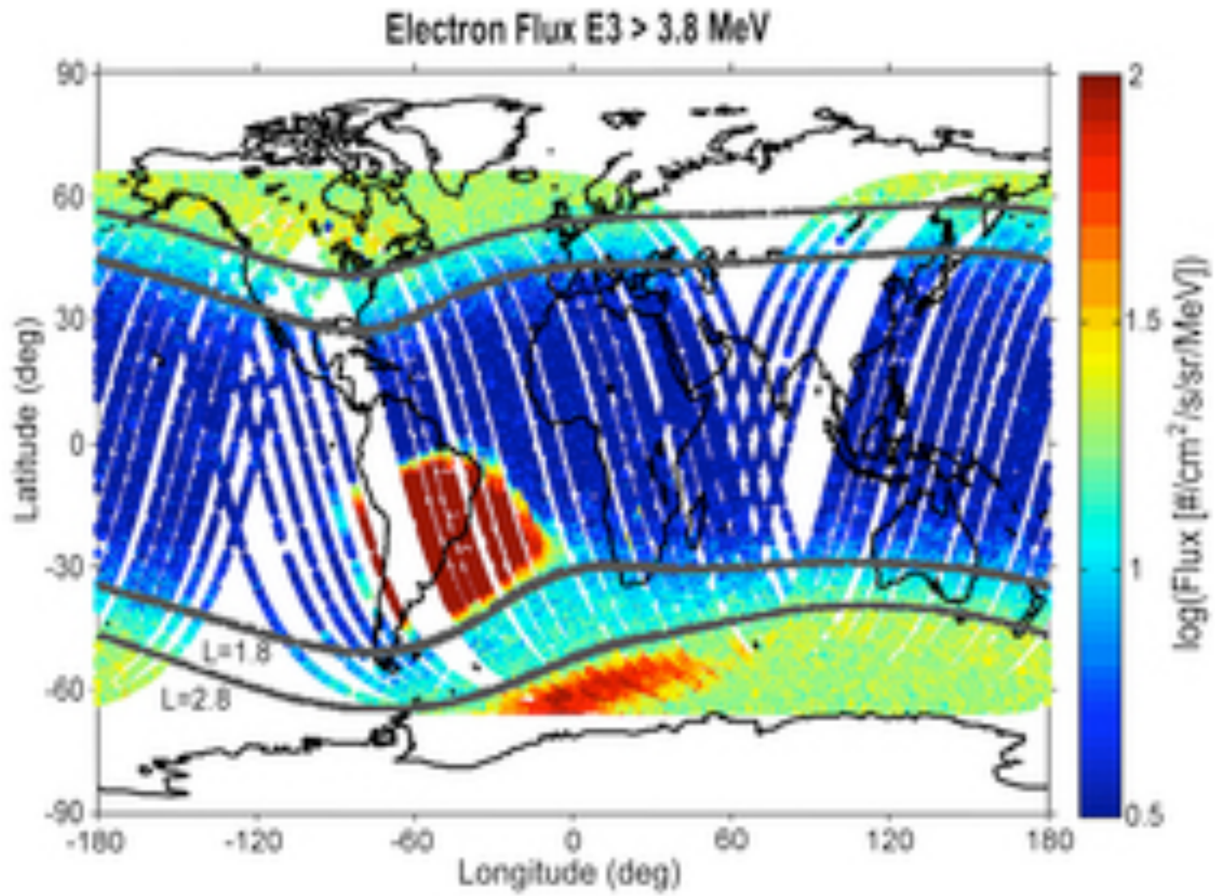
Number of CubeSat Publications



Conclusion: **CubeSats have already produced high-value science, as demonstrated by peer-reviewed publications in high-impact journals. {…}**

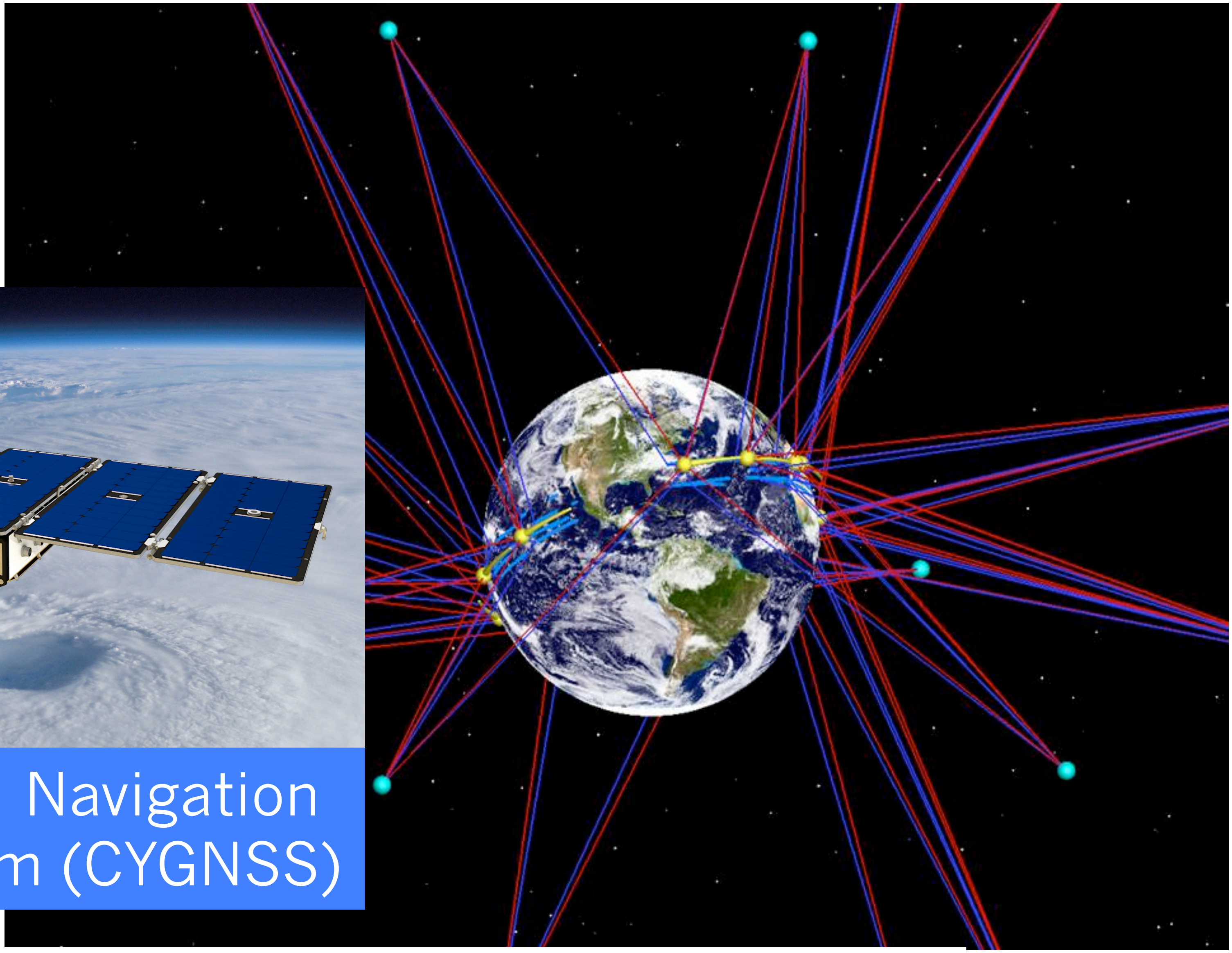
CubeSat Example: High-Risk Orbits, with other Mission

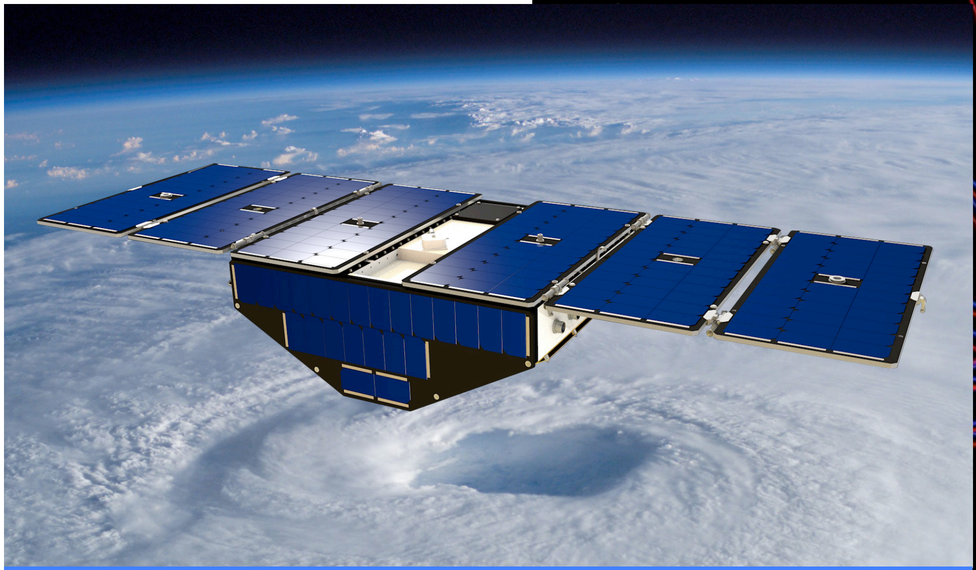




Colorado Student Space Weather Experiment (CSSWE)

Example: Constellations/Swarms





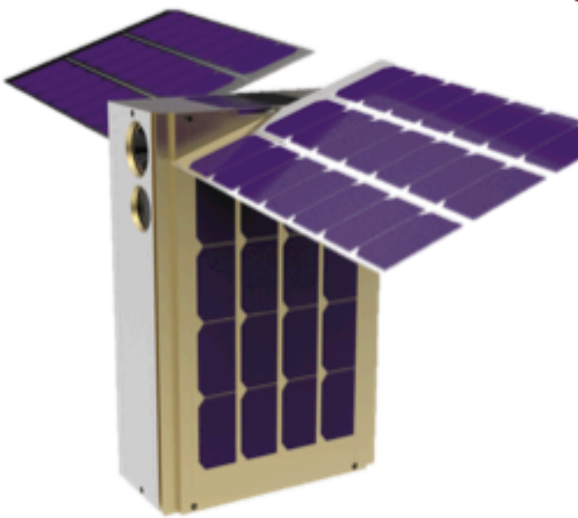
Cyclone Global Navigation Satellite System (CYGNSS)

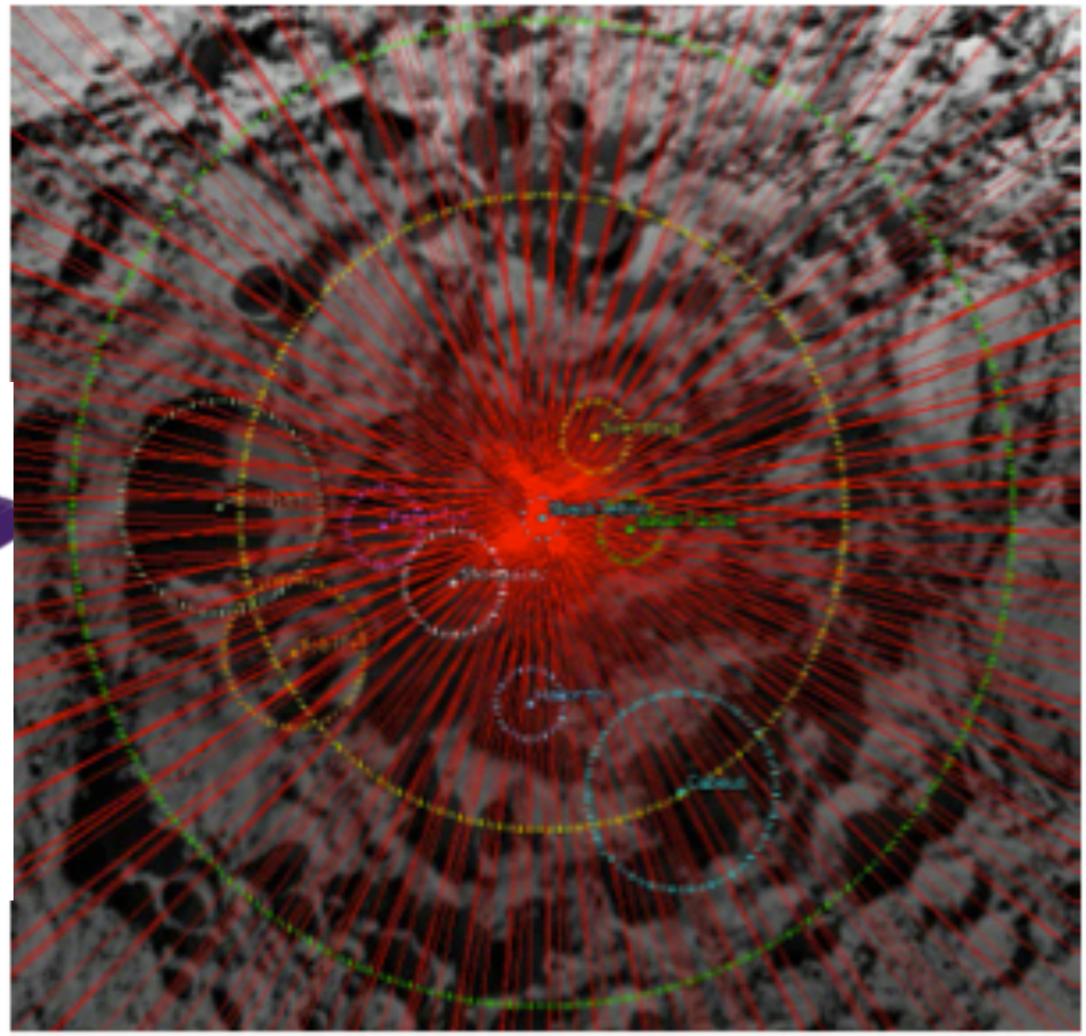
Not a CubeSat, but CubeSat enabled

Planetary CubeSats are a Little Different

- Currently no deep space CubeSats in flight launched by NASA or NSF – no track record of success, no heritage hardware, no lessons learned
- Deep space CubeSat missions can have lower risk tolerance than traditional CubeSats – higher cost, fly-learn-refly paradigm does not apply
- Traditional CubeSat form factor is too restrictive for some planetary applications – aperture size, thermal control issues, radiation environment, long-range communication

Example: Targeted Science: 1 Instrument, 1 Question





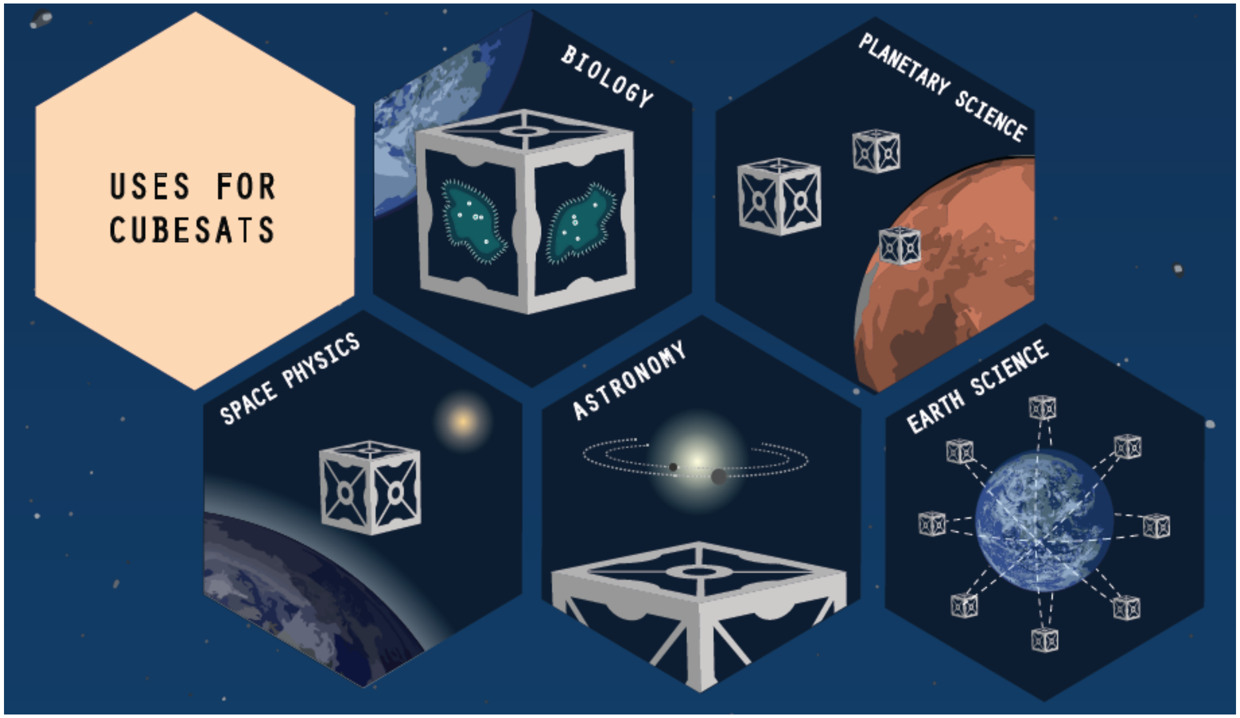
LunaH Map
SIMPLEx Program

Perspective on Planetary CubeSats

- Even though there are no active planetary CubeSats or published science results from CubeSats in planetary science, there is demonstrated interest by the planetary science community, and multiple CubeSats are currently under development.

- **Conclusion:** CubeSats in planetary science have potential in three areas: creating unique vantage points or multi-point measurements, exploring high-risk or uncharted regions; and serving as low-gravity laboratories. However, they can have unique challenges; the traditional form factor may not be appropriate, and there may be lower risk tolerance due to the nature of single mission opportunities and potential risk to a mothership.

High Value Science



Conclusion: CubeSats have already produced high-value science as demonstrated by peer-reviewed publications that address decadal survey science goals. CubeSats are useful as instruments of targeted investigations to augment the capabilities of large missions and ground-based facilities, they are enabling new kinds of measurements, and they may have the potential to mitigate gaps in measurements where continuity is critical.

Important Caveat

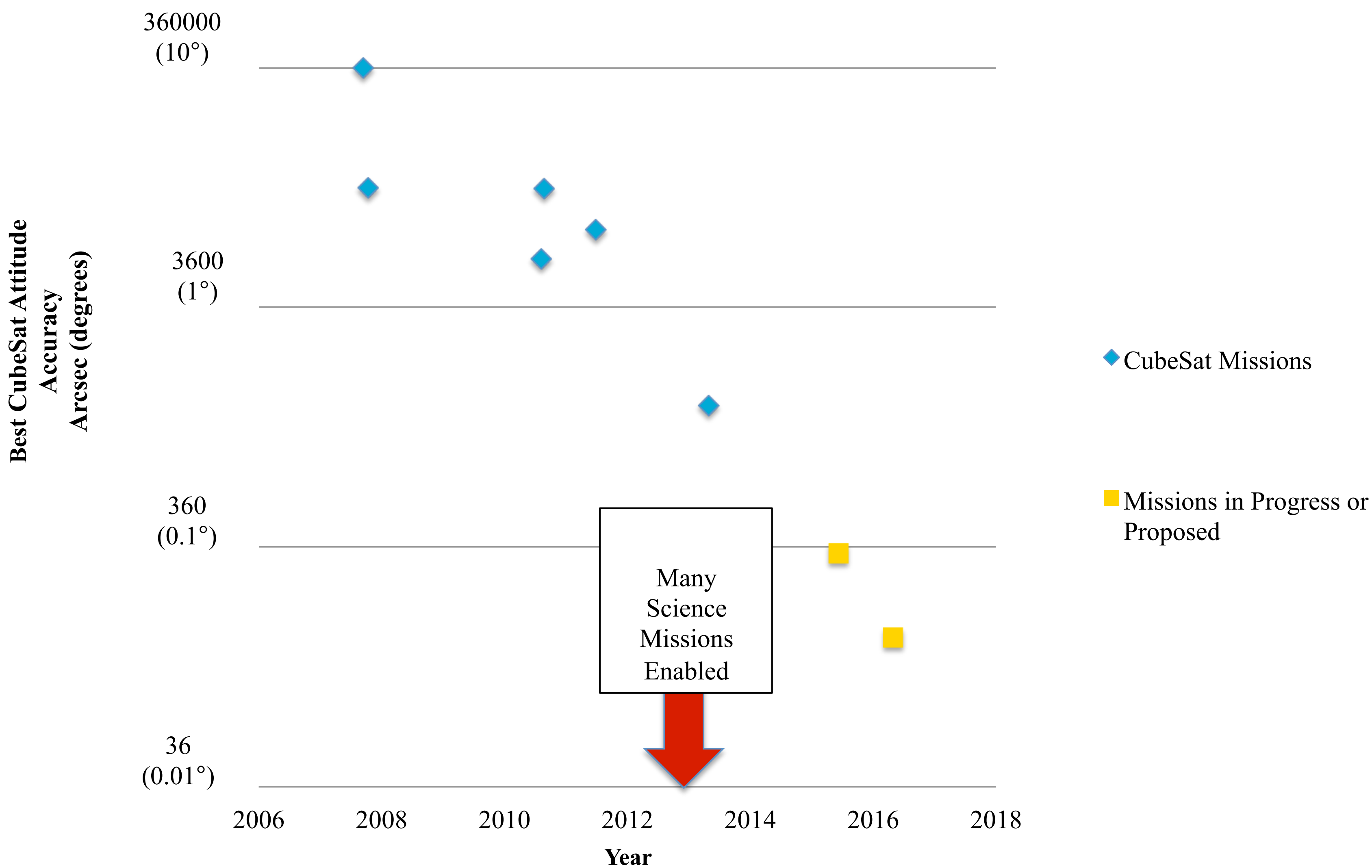
- **Conclusion:** Although all science disciplines benefit from innovative CubeSat missions, CubeSats cannot address all science objectives and are not a low-cost substitute for all platforms. Some activities such as those needing large apertures, high power instruments, or very high precision pointing most likely will always require larger platforms because of fundamental and practical constraints of small spacecraft.

- CubeSats are a specific tool in the suite of options for conducting science.

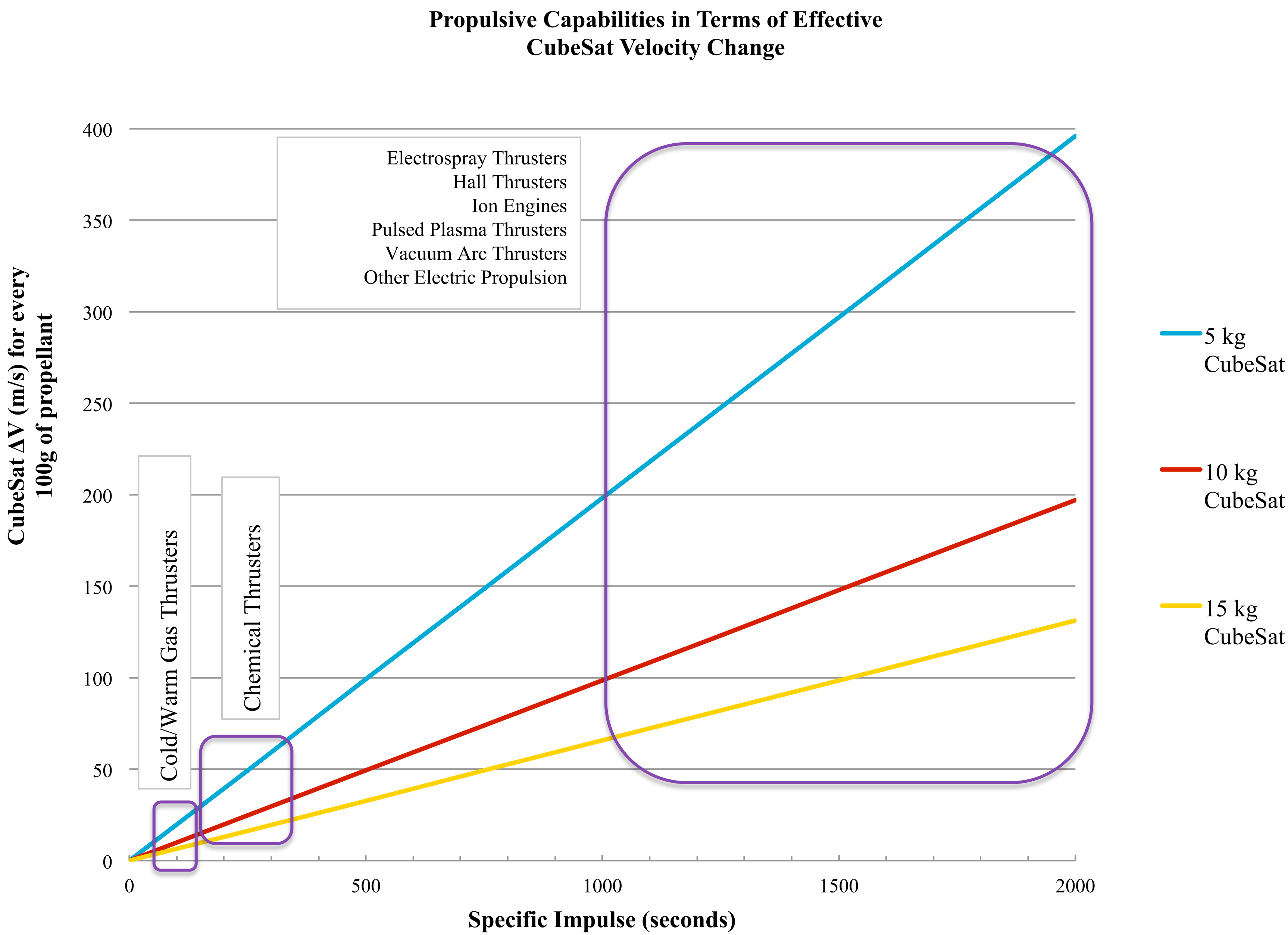
Enabling Technology by Science Discipline

Science Discipline	Enabling Technology	Example Application
Solar and Space Physics	**Propulsion**	Constellation deployment and maintenance, formation flight
	Sub-arcsecond attitude control	High resolution solar imaging
	Communications	Missions beyond low Earth orbit
	Miniaturized field and plasma sensors	In-situ measurements of upper atmosphere plasmas
Earth Science	**Propulsion**	Constellations for high-temporal resolution observation and orbit maintenance
	Miniaturized sensors	Stable, repeatable and calibrated datasets
	Communications	High data rate
Planetary Science	**Propulsion**	Orbit insertion
	Communications, Comm Infrastructure	Direct/indirect to Earth communications
	Radiation-tolerant electronics	Enhanced survival in planetary magnetospheres, long duration flight
	Deployables	Enhanced power generation beyond Mars
Astronomy and Astrophysics	**Propulsion**	Constellations for interferometry, distributed apertures
	Sub-arcsecond attitude control	High resolution imaging
	Communications	High data rate
	Deployables	Increase aperture and thermal control
	Miniaturized sensors	UV and X-ray imaging
Physical and	Thermal control	Stable payload environment

Illustrating Speed of Development: Attitude Control



Propulsion: Multi-Faceted Approach



Policy Issues Considered

- Regulatory framework for CubeSats is nearly identical to that of large spacecraft
- Issues particularly affecting or potentially limiting the development of CubeSats as a science tool
  - Orbital debris
  - Communications
  - Launch vehicles
  - Other restrictions affecting the community, such as ITAR, etc.

Overview (recap)

1. Based on detailed analysis of available data
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Questions, Comments?

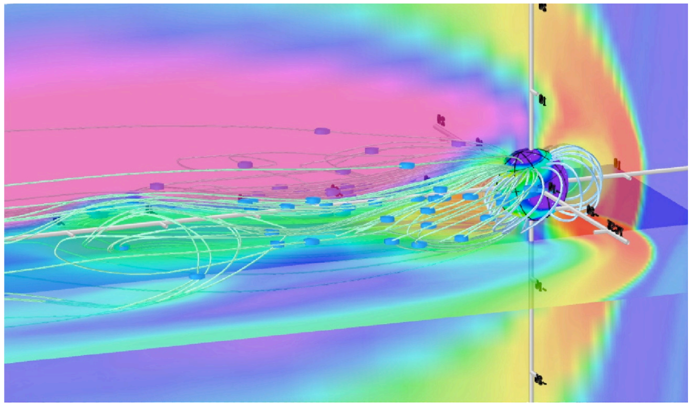
Recommendations (selected)

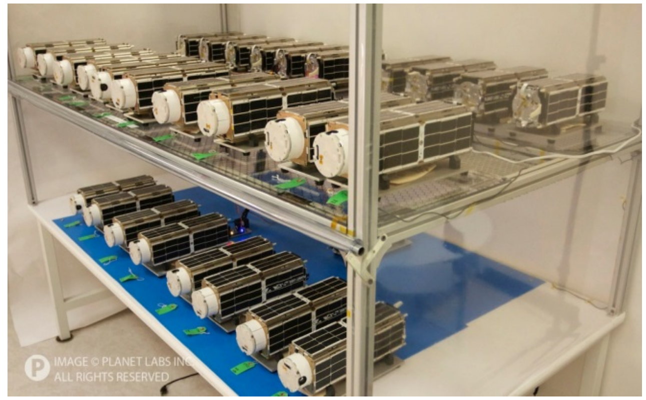
Recommendation Related to Technology

Recommendation: NASA and other relevant agencies should invest in technology development programs in four areas that the committee believes will have largest impact on science missions: high bandwidth communications, precision attitude control, propulsion, and the development of miniaturized instrument technology. To maximize their impact, such investments should be competitively awarded across the community and take into account coordination across different agencies and directorates, including NASA's Science Mission Directorate and Space Technology Mission Directorate, and between different NASA and Department of Defense centers.

- These technology areas were derived from the analysis of the science discipline needs.

Constellations and Swarms





Recommendation: Constellations of 10-100 science spacecraft have the potential to enable critical measurements for space science and related space weather, weather and climate, as well as some for astrophysics and planetary science topics. Therefore, NASA should develop the capability to implement large-scale constellation missions taking advantage of CubeSats or CubeSat-derived technology and a philosophy of evolutionary development.

NASA Management

Recommendation: NASA should develop centralized management of the agency's CubeSat programs for science and science-enabling technology that is in coordination with all directorates involved in CubeSat missions and programs, to allow for more efficient and tailored development processes to create easier interfaces for CubeSat science investigators; provide more consistency to the integration, test, and launch efforts; and provide a clearinghouse for CubeSat technology and vendor information and lessons learned. The management structure should use a lower-cost and streamlined oversight approach that is also agile for diverse science observation requirements and evolutionary technology advances.

NASA Management, 2

Recommendation: NASA should develop and maintain a variety of CubeSat programs with cost and risk postures appropriate for each science goal and relevant science division and justified by the anticipated science return. A variety of programs are also important to allow CubeSats to be used for rapid responses to newly recognized needs and to realize the potential from recently developed technology.

Recommendation Related to the Private Sector

Recommendation: As part of a CubeSat management structure, NASA should analyze private capabilities on an ongoing basis and ensure that its own activities are well coordinated with private developments and determine if there are areas to leverage or that would benefit from strategic partnerships with the private sector.

Best Practices

- *Avoid premature focus*: Although the committee recommends a NASA-wide management structure to create opportunities for new investigators and provide a clearinghouse for information and lessons learned, premature top-down direction that eliminates the experimental, risk-taking programs would slow progress and limit potential breakthroughs.
- *Maintain low-cost approaches as the cornerstone of CubeSat development*: It is critical to resist the creep towards larger and more expensive CubeSat missions. Low-cost options for CubeSats are important, because more constrained platforms and standardization, coupled with higher risk tolerance, tend to create more technology innovation in the long run.
- *Manage appropriately:* As missions grow more capable and expensive, management and mission assurance processes will have to evolve. Yet, it is critical to manage appropriately and not to burden low-cost missions with such enhanced processes, by actively involving CubeSat experts in policy changes and discussions as well as in proposal reviews.