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
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 materialized if a number of conditions are fulfilled
   1. Technology and connections to industry
   2. Policy issues
   3. Programmatic and management issues
US CubeSats Launched – by Mission Type

![Graph showing the number of CubeSats launched by mission type from 2000 to 2015. The categories include Imaging, Communication, Technology, Education, Science, Commercial, NASA, DOD, NSF, and Education. The graph indicates a significant increase in launches after 2010, with a peak in 2014 and 2015.]}
International Participation

- United Kingdom: 4
- South Korea: 4
- Italy: 4
- Germany: 9
- Denmark: 9
- Japan: 18
- All Others: 50
- United States: 327
International Participation, 2

![Graph showing international participation in CubeSats from 2000 to 2015. The graph indicates the number of CubeSats launched by different countries over the years, with a notable increase in 2013. The countries are represented by different colors: Japan, Denmark, Germany, Italy, South Korea, United Kingdom, Netherlands, Norway, Peru, and Singapore.](image-url)
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
74% Engineering Focused
41 Refereed Publications on Science
All science papers reviewed and assessed by committee

Conclusion: **CubeSats have already produced high-value science, as demonstrated by peer-reviewed publications in high-impact journals.**
CubeSat Example for 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
Example: Targeted Science: 1 Instrument, 1 Question

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

Best CubeSat Attitude Accuracy Arcsec (degrees)

- 360000 (10°)
- 3600 (1°)
- 360 (0.1°)
- 36 (0.01°)

Year

- 2006
- 2008
- 2010
- 2012
- 2014
- 2016
- 2018

CubeSat Missions

Many Science Missions Enabled

Missions in Progress or Proposed
Propulsion: Multi-Faceted Approach

Propulsive Capabilities in Terms of Effective CubeSat Velocity Change

CubeSat ΔV (m/s) for every 100g of propellant

- 5 kg CubeSat
- 10 kg CubeSat
- 15 kg CubeSat

Thrusters:
- Electrospray Thrusters
- Hall Thrusters
- Ion Engines
- Pulsed Plasma Thrusters
- Vacuum Arc Thrusters
- Other Electric Propulsion

Chemical Propulsion:
- Cold/Warm Gas Thrusters
- Chemical Thrusters
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.
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Questions, Comments?

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