YOU GET WHAT YOU PAY FOR: EXAMINING THE TRUE COST OF DELIVERING UTILITY WITH SMALL SATELLITES

IAA Symposium on Small Satellites for Earth Observation
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**APL Track Record in Space**

**Innovative, Cost-Effective End-to-End Space Missions**

**Recent Examples:**
- 70+ Spacecraft
- 150+ Sensors & Payloads
- Short time to space
- Modest-sized missions
- Tight requirements process
- Disciplined development

**Critical Challenge:** Answer fundamental space & earth science questions and pursue space solutions to critical military problems
Small-Sat (1U-3U) Landscape: 2007

- Universities and national labs led early development
- Limited “explicit” offerings for systems and components
Exponential Growth in Small-Satellite Missions

Nano/Microsatellite Launch History and Projection (1 - 50 kg)

Projections based on announced and future plans of developers and programs indicate between 2,000 and 2,750 nano/microsatellites will require a launch from 2014 through 2020.

2014 Nano/Microsatellite Market Assessment
A mid-year update
4 August 2014 | Logan, UT

Nano/Microsatellite Trends by Sector (1 – 50 kg)

Commercial sector contributed 64% of 2014 nano/microsatellites

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New Small-Satellite Launch Options Anticipated in FY16

[Image Credit: Spaceflight Services]

[Image Credit: TriSept Corporation]

[Image Credit: Altius Space Machines]

[Image Credit: Generation Orbit Launch Services]

[Image Credit: DARPA]

[Image Credit: Sandia National Lab]

[Image Credit: Stratolaunch Systems]

[Image Credit: Rocket Labs]

[Image Credit: JHU/APL]

[Image Credit: Firefly Space Systems]

[Image Credit: ORS Office]

[Image Credit: Nanoracks/JAXA]

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Smaller Isn’t Necessarily Better...

“SORRY, BIG GUY. WE’RE DOWNSIZING. HERE COMES YOUR REPLACEMENT.”
**Mission Utility vs. Design Trade Space**

### (-) Reduced Science or Mission Goals
- Reduced goals due to:
  1. Lack of collaboration from same or similar instrument
  2. Lack of multi-spectral information
  3. Decreased number of observations yield reduced reliability in outcomes
  4. Reduced life expectancy
  5. Downlink bandwidth and power constrained
  6. If collaboration is needed between space vehicles, the complexity increases

### (+) Reduction of Engineering Issues
- Multi-sensor compatibility issues
  1. Mechanical such as vibration
  2. Electrical (EMI/EMC)
  3. Optical field of view
  4. Thermal

### Trade Space

### Reduction of Programmatic Issues
- Programmatic concerns lessened
  1. Cost and schedule savings (including cost of and time to launch)
  2. Reduced programmatic interfaces
  3. Increased single-sensor functionality and performance

### Reduced Complexity
- Engineering optimization through:
  1. Reduced number of interfaces
  2. Opportunity to provide full support to single payload
### Measuring Physical Phenomenology of Interest

- **Photons, Waves, Particles and Fields?**
  - Present technology limits mostly to single point aperture systems
  - Future technology can push to distributed apertures on smaller platforms

  *Photons from the edge of the universe OR In-situ Measurement of Earth Magnetic Field*

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**Hubble Optical Telescope Assembly (~8 ft D x 21 ft)**

**ST-5 Magnetometer Sensor (~2in x 2in x 1in)**
Market Growth Motivated by Changing Landscape

- Technology advances rapidly redefining the art of the possible
- Large, exquisite systems becoming politically and fiscally unaffordable as exclusive norm → need complementary, “responsive” solutions for augmentation and gapfiller capabilities
- Desire for increased multi-point measurements using formations, swarms, and constellations
- Increasing resiliency, flexibility w/ new arch. (e.g., disaggregation)
- Desire for dedicated/decentralized owner-operator space capabilities
Primary Mission Applications Following the $$

More than half of future nano/microsatellites will be used for Earth observation and remote sensing purposes (compared to 10% in 2013)

Imagery & Video Analysis
- SpaceKnow
- OmniEarth
- Dauria
- Skybox Imaging
- UrtheCast
- Zeta Global
- Allsource Analysis
- ORB Logic
- Mapsearch

Remote Sensing Imaging
- BlackSky Global
- OHB System
- GOHSpace
- SunSpace
- Surrey Satellite Technology
- ISPS
- BlackSky Imagery
- Tyvak
- Planets Labs
- NovaWorks
- Clyde Space

Non-Imaging
- PlanetIQ
- GeoOptics
- Dauria
- Aspire

A smaller proportion of technology development/demonstration nano/microsatellites will be built in 2014 (31% vs. 55% in 2013)

* Please see End Notes 1, 2, 5, and 6.
Visible Imagery Mission at LEO (Example)

What are we looking at? Ok, It’s a road with vehicles? I spy a motorcycle!

What are we looking at?
Ok, It’s a road with vehicles?
I spy a motorcycle!

Sample Scenes
Resolution Scale (m)

What are we looking at?
Ok, It’s a road with vehicles?
I spy a motorcycle!

Sample Scenes
Resolution Scale (m)

Planet Labs @ ISS

Nanosatellite to SmallSat Sizes
Physical Dimensions of CubeSats 1-3U
Example LEO Imagery with 3U CubeSat: Planet Labs
Planet Lab Results: Change Detection & Monitoring

- High temporal revisit with modest resolution underpins value

Drought in Três Marias Reservoir Brazil

Burning Fields, Itumbiara Brazil

Development in Inner Mongolia China

Image Credit: Landsat (July 2013)

Image Credit: Landsat 8 (August 8, 2014)

Image Credit: Landsat (June 2013)

Image Credit: Planet Labs (July 31, 2014)

Image Credit: Planet Labs (August 9, 2014)

Image Credit: Planet Labs (July 6, 2014)
Example LEO Comms w/ 3U CubeSat: ORS Tech 1&2

- Launched at 2015 EST on Nov. 19, 2013
  - ORS-3 mission orbit: 500 km x 40.5°
  - Designated ORS Tech 1 & 2 (two of 29 deployed payloads)

- Contact made with both vehicles on 1st APL pass ~100 mins after launch

- Commissioned normal mode 23-24 Nov.

- Utilized automated mission operations C2 from APL and remote facilities

- Successfully satisfied all program objectives and 24/24 mission-level requirements
  - Conducted extensive system testing and characterization

- Both satellites had naturally de-orbited after 16.5 months
ORS Tech 1 & 2 Ground Access Analysis

- Orbit: 500 km x 40.5°
- Simulated for one year
- Minimum contact duration: 30 sec
- The contours correspond to the accessible ground footprints for communication links subject to elevation constraints

<table>
<thead>
<tr>
<th>Master Gateway (JHU/APL)</th>
<th>5 deg</th>
<th>10 deg</th>
<th>30 deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access Length, sec</td>
<td>Min</td>
<td>Max</td>
<td>Mean</td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>587</td>
<td>514</td>
</tr>
<tr>
<td>Time Between Accesses, hr</td>
<td>1.6</td>
<td>16.9</td>
<td>4.1</td>
</tr>
<tr>
<td>Accesses per Day</td>
<td>5</td>
<td>7</td>
<td>5.6</td>
</tr>
<tr>
<td>Doppler, kHz</td>
<td>-8.2</td>
<td>8.2</td>
<td>0</td>
</tr>
</tbody>
</table>
ORS Tech Constellation Revisit: 650 km x 50° (ε ≥ 30°)

- Small LEO constellations can provide meaningful access and global coverage
  - Driven by effective field of regard, beamwidth (~60°)
  - Launch access to diverse orbit geometries
  - Operational considerations, tempo notwithstanding
    - E.g., power, C2 access
- 50+ satellites required to achieve (near) continuous coverage from LEO
  - Scales with minimum revisit period

Planet Labs Dove constellation requires >10x more for same results
Design and Development from Bottoms-Up

- Asymmetry in design scaling: challenging and expensive to try and make a big design, small; but not vice-versa (to a limit)
- Limited capacity for over-design as size shrinks
- A holistic, bottoms-up approach is needed
APL Enablers for Executing Small System Missions

Low SWaP payloads and subsystem technologies for free-flyers and hosted manifest

Detailed Understanding of Space Environment, Effects, Test, Mitigation

Rideshare Adapter Systems

Responsive, End-to-End Mission System Engineering

Flexible, High Reliability, Flight Qualified Portfolio of Multi-Mission Nanosatellite (MMN) Platforms

Highly-Automated, Globally Networked Mission Operations C2 Systems

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**Multi-Mission Nanosatellite Design Summary**

- High reliability spacecraft portfolio builds increasing system capability and payload accommodation around core design
  - Rich avionics based on NASA Solar Probe Plus processor
  - Heritage (RBSP) flight/ground SW utilizing Core Flight Executive (CFE)
  - Significant onboard processing, autonomy, and resiliency features
  - Enabling subsystem components: Mini-SDR, GPS navigation system
  - Interface to robust ground system test environment

Utilize as proxy reference designs to analyze reliability and cost

<table>
<thead>
<tr>
<th>FEATURE</th>
<th>MMN-3U</th>
<th>MMN-6U</th>
<th>EXPRESS w/ Propulsion</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Payload</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass (Max)</td>
<td>1.5 kg (5.0 kg SV NTE)</td>
<td>4 kg (12 kg SV NTE)</td>
<td>20 kg (75 kg NTE)</td>
</tr>
<tr>
<td>Volume (Max)</td>
<td>95 x 95 x 85 mm (0.85U)</td>
<td>95 x 115 x 220 mm (2.4U)</td>
<td></td>
</tr>
<tr>
<td><strong>GN&amp;C</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attitude Sensors</td>
<td>Magnetometer and Sun Sensors (12)</td>
<td>Star Tracker, Magnetometer, Sun Sensors (6)</td>
<td>Star Trackers (2), Magnetometer, Sun Sensors (6)</td>
</tr>
<tr>
<td>Attitude Knowledge</td>
<td>&lt; 5 deg</td>
<td>&lt; 0.1 deg</td>
<td>&lt; 0.01 deg</td>
</tr>
<tr>
<td>Attitude Actuators</td>
<td>Torque Coils (3) + Reaction Wheel (1)</td>
<td>Torque Rods (3) + Reaction Wheels (3)</td>
<td>Torque Rods (3) + Reaction Wheels (3/4) + Thrusters (4/8)</td>
</tr>
<tr>
<td>Attitude Control</td>
<td>&lt; 10 deg</td>
<td>&lt; 1.0 deg</td>
<td>&lt; 0.1 deg</td>
</tr>
<tr>
<td>Orbit Knowledge</td>
<td>GPS-based; ground processed</td>
<td>GPS-based; real-time</td>
<td>GPS-based; real-time</td>
</tr>
<tr>
<td><strong>Propulsion</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delta-V Capability</td>
<td>N/A</td>
<td>&gt; 25 m/s (Option)</td>
<td>&gt; 150 m/s</td>
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<tr>
<td><strong>Power</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>P/L Available Orbit Average</td>
<td>1-2 W</td>
<td>5 W</td>
<td>20 W</td>
</tr>
<tr>
<td>P/L Available Peak</td>
<td>40 W for 10 min/orbit (10% duty cycle)</td>
<td>40 W for 20 min/orbit (20% duty cycle), TBC</td>
<td>100 W for 10 min/orbit (10% duty cycle)</td>
</tr>
<tr>
<td><strong>Comms</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline Data Rate</td>
<td>1200 bps</td>
<td>2 Mbps</td>
<td>2 Mbps with X-Band D/L at 100 Mbps (Option)</td>
</tr>
<tr>
<td>Data Privacy</td>
<td>AES-256</td>
<td>AES-256</td>
<td>AES-256</td>
</tr>
<tr>
<td>Type-I Encryption?</td>
<td>No</td>
<td>Yes (Lite)</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Reliability Block Diagram (MMN-6U Example)

- Design estimated 86% mean mission (functional) reliability after one year
  - 68% mean full system reliability (i.e., no failures)
  - Limited empirical data for GNC components are the drivers

- Two-ball system flown for operational redundancy improves mission reliability to 98%

- Reliability models typically do not capture design failures, software failures, operator errors, or improper build, assembly & workmanship issues
  - Motivates implementing a strong test and design verification plan
## Parametric Costing Results for Reference S/C Designs

- Three trusted models used to evaluate total spacecraft cost through PSR (no launch or ops):
  - Industry standard Price H (calibrated with NASA/USAF data)
    - Highly configurable, considers TRL
  - Aerospace Corporation Small-Satellite Cost Model (SSCM)
  - APL model derived from historic empirical data ($/kg)
- Presume system is delivered by an experienced satellite mission integrator
- Wide dispersion of results indicate limitations of models to consistently estimate low mass systems

<table>
<thead>
<tr>
<th>Mass (kg) TRL</th>
<th>PRICE H</th>
<th>$/kg</th>
<th>SSCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Express 58.63</td>
<td>$26,544</td>
<td>$12,742</td>
<td>$7,985</td>
</tr>
<tr>
<td>C&amp;DH 3.60</td>
<td>$9,247</td>
<td>$4,531</td>
<td>$396</td>
</tr>
<tr>
<td>EPS 17.72</td>
<td>$5,101</td>
<td>$3,279</td>
<td>$1,238</td>
</tr>
<tr>
<td>GN&amp;C 6.03</td>
<td>$2,782</td>
<td>$2,590</td>
<td>$2,729</td>
</tr>
<tr>
<td>Propulsion 11.51</td>
<td>$3,458</td>
<td>$2,502</td>
<td>$526</td>
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<tr>
<td>T&amp;C 2.03</td>
<td>$1,379</td>
<td>$2,549</td>
<td>$204</td>
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<tr>
<td>Mech&amp;Struct 15.65</td>
<td>$3,346</td>
<td>$1,116</td>
<td>$1,937</td>
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<tr>
<td>Thermal 2.09</td>
<td>$1,231</td>
<td>$1,977</td>
<td>$955</td>
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<tr>
<td>6U 9.38</td>
<td>$11,084</td>
<td>$2,428</td>
<td>$3,269</td>
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<tr>
<td>C&amp;DH 1.39</td>
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<td>$1,755</td>
<td>$744</td>
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<tr>
<td>EPS 2.11</td>
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<td>$337</td>
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<tr>
<td>GN&amp;C 0.70</td>
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<tr>
<td>T&amp;C 0.70</td>
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<td>Thermal 0.08</td>
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<tr>
<td>3U 4.02</td>
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<tr>
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<tr>
<td>EPS 1.59</td>
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<td>$294</td>
<td>$283</td>
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<tr>
<td>GN&amp;C 0.30</td>
<td>$289</td>
<td>$127</td>
<td>$348</td>
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<tr>
<td>T&amp;C 0.41</td>
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<td>$390</td>
<td>$204</td>
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<tr>
<td>Mech&amp;Struct 1.26</td>
<td>$706</td>
<td>$105</td>
<td>$199</td>
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<tr>
<td>Thermal 0.09</td>
<td>$61</td>
<td>$7</td>
<td>$88</td>
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### Cost Estimates (FY15$K)

<table>
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<tr>
<th>Mass (kg) TRL</th>
<th>C&amp;DH</th>
<th>EPS</th>
<th>GN&amp;C</th>
<th>T&amp;C</th>
<th>Mech&amp;Struct</th>
<th>Thermal</th>
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<td>Thermal 0.09</td>
<td>$548</td>
<td>$105</td>
<td>$199</td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>$47</td>
<td>$7</td>
<td>$88</td>
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</table>
### Parametric S/C Cost Estimates Across All Models

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<th>Mission Elements</th>
<th>3U</th>
<th>6U</th>
<th>Express</th>
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</thead>
<tbody>
<tr>
<td>PM</td>
<td>$0.14</td>
<td>$0.20</td>
<td>$0.41</td>
</tr>
<tr>
<td>SE</td>
<td>$0.13</td>
<td>$0.20</td>
<td>$0.40</td>
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<tr>
<td>MA</td>
<td>$0.12</td>
<td>$0.18</td>
<td>$0.36</td>
</tr>
<tr>
<td>Spacecraft (QTY1)</td>
<td>$2.12</td>
<td>$3.03</td>
<td>$7.12</td>
</tr>
<tr>
<td>I&amp;T</td>
<td>$0.69</td>
<td>$1.16</td>
<td>$1.26</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$3.20</strong></td>
<td><strong>$4.77</strong></td>
<td><strong>$9.54</strong></td>
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<table>
<thead>
<tr>
<th>1st Unit</th>
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<tbody>
<tr>
<td>PM</td>
</tr>
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<td>MA</td>
</tr>
<tr>
<td>Spacecraft (QTY1)</td>
</tr>
<tr>
<td>I&amp;T</td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>

- Results reflect non-recurring engineering associated with new mission formulation and development (no payload included)
- Includes non-negligible management, system engineering, safety mission assurance, and integration costs along with those to produce the spacecraft itself
- Presumes design decisions consider total lifecycle cost, including support for I&T activities and mission operations

Savings realized by subsystem re-use between platforms typically applied to additional design complexity to increase performance/capability.
Applying Learning Curve for Small-Satellite Production

- Considers expected reduction of unit costs for large quantity production
  - Draws from historic building experience to determine expected reductions in labor and materials costs through staff learning:
    - Increasing yields, operation throughput, improved tooling, substituting equipment for labor, eliminating unnecessary steps, process improvement, and substitution
- Most dramatic gains realized with processes dominated by hand assembly:
  - 50% hand assembly with 50% machining = 85% learning curve
Quantity Production: Results and Model Disconnects

- PM, system engineering, MA elements (generally) amortize with scale
- Spacecraft cost floor typically constrained by vendors costs and bill of materials (BOM)
  - Presumes strong supply chain with timely delivery of qualified parts/components
  - Incentive to vertically integrate for large-scale production (if feasible)
- I&T costs do not reflect learning gains, streamlined methods, automation
  - Most likely area of realizable savings

<table>
<thead>
<tr>
<th>Mission Elements</th>
<th>100th Unit (Concurrent Build)</th>
<th>Cost Range (FY15$M)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3U</td>
<td>6U</td>
</tr>
<tr>
<td>PM</td>
<td>$ 0.07</td>
<td>$ 0.11</td>
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<tr>
<td>SE</td>
<td>$ 0.07</td>
<td>$ 0.11</td>
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<tr>
<td>MA</td>
<td>$ 0.06</td>
<td>$ 0.10</td>
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<tr>
<td>Spacecraft (QTY1)</td>
<td>$ 0.90</td>
<td>$ 1.29</td>
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<tr>
<td>I&amp;T</td>
<td>$ 0.55</td>
<td>$ 0.93</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$ 1.66</td>
<td>$ 2.53</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Mission Elements</th>
<th>100th Unit (Concurrent Build)</th>
<th>Cost Range (FY15$M)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3U</td>
<td>6U</td>
</tr>
<tr>
<td>PM</td>
<td>$ 0.03</td>
<td>$ 0.05</td>
</tr>
<tr>
<td>SE</td>
<td>$ 0.03</td>
<td>$ 0.05</td>
</tr>
<tr>
<td>MA</td>
<td>$ 0.03</td>
<td>$ 0.05</td>
</tr>
<tr>
<td>Spacecraft (QTY1)</td>
<td>$ 0.11</td>
<td>$ 0.15</td>
</tr>
<tr>
<td>I&amp;T</td>
<td>$ 0.55</td>
<td>$ 0.93</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$ 0.75</td>
<td>$ 1.23</td>
</tr>
</tbody>
</table>

85% Learning

50% Learning
Small-Satellite (< 200 kg) Constellations Are Coming!

- Seeking to provide global, multi-point, high temporal access/coverage with periodic refresh

Lab/Academia
- Small (2-10): Science/military pathfinder; regional
- Medium (20-50): Science/military IOC, commercial pathfinder; global

Industry
- Large-scale (100+): All sectors FOC; global

- Production engineering, highly automated assembly critical enablers to achieve tractable cost points, ROI

- Effective large-scale production gains predicated upon
  - Some level of minimum flow to maintain throughput efficiencies
  - Modest ability to accommodate changes to design baseline
Conclusions and Next Steps

- Small satellite missions must consider total mission value
  - Employ disciplined system engineering to ensure mission objectives and requirements are suitable, sufficient, and can be verified
  - Implement design, functional redundancy (to the extent possible); test
  - Delivering utility sufficient to satisfy the value proposition to user/market
  - Full accounting of total life-cycle cost across all architecture elements

- Scalability is essential for moving from pathfinder/prototype to constellations: entire architecture must be considered

- New methods for increasing production efficiency will enable new mission concepts and approaches
  - Reduced non-recurring engineering

- Production engineering and automated I&T methods to support large-scale missions/constellation can yield significant price savings
  - Discounts not proportional for smaller missions (minimum PM/SE/SMA)
  - Typically focused design space; changes to baseline can be costly
  - Investment must be made to establish and validate process/systems

- Capability-driven need for both lab/academia and industry-led missions
  - Partnerships and tech-transfer will be advantageous for scaling to larger scales