Can Small Satellites Satisfy Such Requirements?

- Make possible accurate predictions of solar phenomena throughout the solar system
- Enable accurate environmental predictions, including weather, climate, natural and human induced events
- Explore habitable environments across the solar system with human and robotic explorers
- Are we alone? How did we get here? How does the universe work?
Strategically Planned Science-Driven Missions

New Earth Science Decadal Survey now in planning stages

Astrophysics

Earth Science

Heliophysics

Planetary

Organized by the National Academies on behalf of NASA establishing USA national priorities for scientific observations, as identified by the community, within a 10-year time frame.

2012 – 2021

2007 – 2016

2012 – 2021

2013 – 2022
SMD Technology Overview

Nearly all of SMD’s missions introduce new capabilities and push the state of the art in science instruments or platform technologies.

Strategic technology investments must be coordinated across the Agency and are critical for the success of future missions.

The SMD Technology Federation was established to provide the necessary cross-Agency coordination and to provide advice to the SMD Associate Administrator.
## Overview of SMD Technology Programs

<table>
<thead>
<tr>
<th>Program Name</th>
<th>FY16 Budget (approx, millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO)</td>
<td>$6.7</td>
</tr>
<tr>
<td>Maturation of Instruments for Solar System Exploration (MatISSE)</td>
<td>$14.3</td>
</tr>
<tr>
<td>Mars Technology</td>
<td>$5.0</td>
</tr>
<tr>
<td>Icy Satellites Surface Technology</td>
<td>$25.0</td>
</tr>
<tr>
<td>Advanced Technology</td>
<td>$36.0</td>
</tr>
<tr>
<td>Advanced Power Systems</td>
<td>$26.7</td>
</tr>
<tr>
<td>Planetary Science and Technology Through Analog Research</td>
<td>$5.0</td>
</tr>
<tr>
<td>Heliophysics - Technology and Instrument Development for Science (H-TIDeS)</td>
<td>$15.0</td>
</tr>
<tr>
<td>Instrument Incubator (IIP)</td>
<td>$28.3</td>
</tr>
<tr>
<td>Advanced Component Technology (ACT)</td>
<td>$6.5</td>
</tr>
<tr>
<td>In-Space Validation of Earth Science Technologies (InVEST)</td>
<td>$9.5</td>
</tr>
<tr>
<td>Advanced Information Systems Technology (AIST)</td>
<td>$14.3</td>
</tr>
<tr>
<td>Astrophysics Research and Analysis Program (APRA), see note below</td>
<td>$46.2</td>
</tr>
<tr>
<td>Strategic Astrophysics Technology (SAT)</td>
<td>$18.9</td>
</tr>
<tr>
<td>Nancy Grace Roman Technology Fellowships</td>
<td>$1.4</td>
</tr>
<tr>
<td><strong>Total SMD Technology Programs</strong></td>
<td><strong>$258.8</strong></td>
</tr>
</tbody>
</table>

APRA includes approximately 50% from balloons & sounding rocket programs

Technology programs enable competed and strategic missions

- Insight
- Mars 2020
- IRIS
- MMS
- CYGNSS
- SMAP
- ASTRO-H
- WFIRST
Planetary Science Technology Programs

Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO, ~$6.7M/yr)
- Low-TRL technologies
- Funds instrument feasibility studies, concept formation, proof-of-concept instruments, and advanced component technology.

Maturation of Instruments for Solar System Exploration (MatISSE, $14.3M/yr)
- Mid-TRL technologies
- Enables timely and efficient infusion of technology into planetary science missions.

Planetary Science and Technology through Analog Research (PSTAR, ~$5M/yr)
- Technologies that support science investigations
- Focus on identification of life

<table>
<thead>
<tr>
<th>Technology Priorities</th>
<th>PICASSO (Low TRL)</th>
<th>MatISSE (Mid TRL)</th>
<th>PSTAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimization, low power, passively-cooled for all</td>
<td>Sample acquisition and handling techniques</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PSD instruments, particularly in situ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low mass, miniature LIDARS and RADARS</td>
<td>Sample manipulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advanced, miniature sub-millimeter spectrometers</td>
<td>Mobile science platforms</td>
<td></td>
<td></td>
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<tr>
<td>Novel life detection instruments</td>
<td></td>
<td>Autonomous operations</td>
<td></td>
</tr>
<tr>
<td>Outer planet probe instruments</td>
<td></td>
<td>Self-contained deployment systems</td>
<td></td>
</tr>
<tr>
<td>High resolution UV spectrometers</td>
<td></td>
<td>Intelligent systems, human/robotic interfaces</td>
<td></td>
</tr>
</tbody>
</table>
## Outer Planets Capabilities Assessment

<table>
<thead>
<tr>
<th>Technology</th>
<th>Near-Term Missions</th>
<th>Mid-Term Missions</th>
<th>Far-Term Missions</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-Space Propulsion</td>
<td>Europe Flyby</td>
<td>Europe Lander</td>
<td>Enceladus Plume</td>
</tr>
<tr>
<td>Acrocapture / Aeropress</td>
<td></td>
<td>Titan Lander Discovery</td>
<td>Pluto Orbiter &amp; Lander</td>
</tr>
<tr>
<td>Entry</td>
<td></td>
<td>Saturn Probe</td>
<td>Neptune Orbiter &amp; Probe</td>
</tr>
<tr>
<td>Descent and Deployment</td>
<td></td>
<td>Uranus Orbiter &amp; Probe</td>
<td></td>
</tr>
<tr>
<td>Landing</td>
<td></td>
<td>Saturn System</td>
<td></td>
</tr>
<tr>
<td>Aerial Platforms</td>
<td></td>
<td>Europa Advanced Lander</td>
<td></td>
</tr>
<tr>
<td>Landers - Short Duration</td>
<td></td>
<td>To Observer</td>
<td></td>
</tr>
<tr>
<td>Landers - Long Duration</td>
<td></td>
<td></td>
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<tr>
<td>Mobile Platform</td>
<td></td>
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<tr>
<td>Planetary Protection</td>
<td></td>
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<tr>
<td>Energy Storage - Batteries</td>
<td></td>
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<tr>
<td>Energy Generation - Solar</td>
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<tr>
<td>Energy Generation - Radioisotope Power</td>
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<td></td>
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<tr>
<td>Energy Generation - Alternative Sources</td>
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<tr>
<td>Thermal Control - Passive</td>
<td></td>
<td></td>
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<tr>
<td>Thermal Control - Active</td>
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<tr>
<td>Red Hard Electronics</td>
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<td></td>
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<tr>
<td>Cold Temperature Mechanisms</td>
<td></td>
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<tr>
<td>Cold Temperature Electronics</td>
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<td></td>
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<tr>
<td>Communications</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Autonomous Operations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Guidance, Navigation, and Control</td>
<td></td>
<td></td>
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<tr>
<td>Remote Sensing - Active</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remote Sensing - Passive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Probe - Aerial Platform</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>In Situ Surface - Short Duration</td>
<td></td>
<td></td>
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<tr>
<td>In Situ Surface - Long Duration - Geophysical</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Sampling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In Situ Surface - Long Duration - Mobile Lab</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TRL Levels:**
- **TRL 6**: High TRL with funding
- **High TRL**: limited funding, development
- **Mid-TRL**: major investment needed
- **Low TRL**: major investment needed
Planetary Science Technology Working Group assessing currently-identified technology gaps and will make recommendations for near-term investments.

**Early Mission Technologies**
- Entry, Descent, Landing
- Landers - Short Duration
- Battery Storage
- Passive Thermal Control
- Radiation Hardened Electronics
- Cold Temperature Mechanisms
- Autonomy
- Guidance, Navigation, and Control
- In Situ Instruments
- Planetary Protection

**Advanced Mission Technologies**
- Entry, Descent, Landing
- Landers - Long Duration
- Battery Storage
- Passive Thermal Control
- Radiation Hardened Electronics
- Cold Temperature Mechanisms
- Autonomy
- Guidance, Navigation, and Control
- In Situ Instruments
- Planetary Protection
- Mobile Surface Platforms
- Radioisotope Power
- Cold Temperature Electronics
- Communications
- In Situ Surface - Suborbital Platforms

Immediate need - augmentation of Europa mission(s)
Alternative Paradigms for Enabling Science

- NASA budget constraints are limiting the cadence of new missions
- Cost and risk increase due to the exaggerated impact of the potential loss of a single mission, likely delaying science return
- Recent advances in miniaturization of instruments and platforms may ease the cycle of larger and fewer expensive missions, where appropriate, while still achieving the science requirements

Anticipated Benefits of Future SMD Small Sat Science Missions

- Lower costs
- More rapid development
- Higher risk tolerance
- Standardized launch interfaces
- “Build-test-fly” approach possible
- Lower barriers to entry for universities and small businesses
- Greater use of off-the-shelf components
- Possibilities for unique applications (i.e., constellations)

LandSat 8
Launch Mass: 2,071 kg
Instruments: Operational Land Imager (9 bands + panchromatic) and Thermal Infrared Sensor (2 bands)
Spectral Resolution: 15-100 meters (pending frequency)
Development to Launch: 2002 - 2013
Manufacturers: GSFC, Ball Aerospace, Orbital Sciences
Spectrum of Satellite Development

SMD/STMD Studies Focus on Decadal Science from U-Class & ESPA-Class

**U-Class (CubeSat) / MicroSat**
- **CP-6**
  - 10 – 50 cm (linear)
  - 1 – 100 kg
  - 5 – 50 W
  - $1 – 30 million (2015)

**MiniSat / ESPA-Class**
- **LCROSS**
  - 2 meters (linear)
  - 585 kg (dry mass)
  - 600 W
  - $79 million (2009)

**Medium-Class**
- **SMAP**
  - 9.7 meters (linear)
  - 944 kg
  - 550 W (radar peak)
  - $916 million (2015)

**Large-Class**
- **SOHO**
  - 4.3 meters (linear)
  - 1850 kg
  - 1,500 W
  - $1,100 million (1995)

**Flagship-Class**
- **Aura**
  - 17.37 meters (linear)
  - 2,967 kg
  - 4,600 W
Confronting the Barriers

Platform Technology Gaps

Addressed by STMD along with partners in academia and private industry

• Power
• Thermal control
• High speed communications
• Precision pointing

• Propulsion
• On-board processing
• Ground system architectures and standards
• “Swarm” technologies

Instrument Technology Gaps

Addressed by SMD along with partners in academia and private industry

Miniaturization of science instruments in likely feasible areas¹:
Sounders, imagers, radiometers, gravity instruments, magnetic field instruments, ocean color instruments, radars, chemical and biological sensors

Studies

• SMD-led NRC study on Achieving Science Goals Though CubeSats
• Internal SMD small satellite studies (Earth, Heliophysics completed)

SMD/STMD Study of New Opportunities for Low-Cost Science Instruments, Platforms, and Mission Architectures

Joint SMD/STMD study initiated in February 2015 with key goals:

- Investigate current paradigm shifts in the miniaturization of science instruments and disruptive small satellite platform technologies
- Determine the potential for novel approaches that could break the cycle of “larger but fewer” expensive missions
- Identify key SMD science measurement requirements that could be satisfied through such paradigms
- Identify technology gaps that could be addressed through solicitations such that barriers to alternative paths are removed

Study Timeline

<table>
<thead>
<tr>
<th>Category</th>
<th>Timeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth Science</td>
<td>Spring / Summer 2015</td>
</tr>
<tr>
<td>Heliophysics</td>
<td>Summer / Fall 2015</td>
</tr>
<tr>
<td>Planetary Science</td>
<td>2016</td>
</tr>
</tbody>
</table>
### Study Results - Earth Science

**Classifying potential instrument/measurement options from SmallSat Study**

<table>
<thead>
<tr>
<th>Mission</th>
<th>SmallSat Instrument</th>
<th>SmallSat Capable</th>
<th>Architecture</th>
<th>Key Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>CloudSat</td>
<td>Cloud Profiling Radar</td>
<td>Potentially Yes: ESPA+</td>
<td>Constellation</td>
<td>2m deployable antenna, high power system</td>
</tr>
<tr>
<td>GACM</td>
<td>UV/VIS/SWIR Spectrometer, microwave limb sounder</td>
<td>Yes: 12U to ESPA</td>
<td>Constellation</td>
<td>Differential absorption LIDAR</td>
</tr>
<tr>
<td>GEO-CAPE</td>
<td>UV/VIS/NIR Wide Area and event imaging spectrometer, TIR radiometer</td>
<td>Yes: Hosted Payload, Propulsive ESPA</td>
<td>Constellation</td>
<td>UV-NIR wide field imaging spectrometer</td>
</tr>
<tr>
<td>GPM Core</td>
<td>3D dual precipitation radar (Ka/Ku) with multichannel microwave imager</td>
<td>Yes: Ka-band/microwave No: Ku-band radar</td>
<td>Constellation</td>
<td>Ku-band narrow pulse precipitation radar</td>
</tr>
<tr>
<td>HyspIRI</td>
<td>Visible-shortwave infrared spectrometer and thermal infrared imager</td>
<td>Yes: Pegasus Mini Satellites</td>
<td>Instruments on separate platforms</td>
<td>Compact Dyson spectrometer</td>
</tr>
<tr>
<td>NISAR</td>
<td>Circularly Polarized SAR (CP-SAR) at L-band</td>
<td>Probably Not: ESPA</td>
<td>Repeat Pass or Constellation</td>
<td>2m x 5m deployable antenna</td>
</tr>
<tr>
<td>SMAP</td>
<td>Wide swath shared aperture radar/radiometer</td>
<td>No</td>
<td>N/A</td>
<td>Wide swath shared aperture measurement</td>
</tr>
<tr>
<td>SWOT</td>
<td>Long baseline Ka-band radar</td>
<td>Probably Not: ESPA+</td>
<td>Repeat Pass or Constellation</td>
<td>Precision formation flying, on-board interferometry</td>
</tr>
</tbody>
</table>
### Decadal-Class Science Measurement Requirements

**Comparing measurement drivers and alternative approaches - Earth Science**

<table>
<thead>
<tr>
<th>Mission</th>
<th>Driving Requirement</th>
<th>Alternative Architecture</th>
<th>Enabling Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>QuickScat</td>
<td>Ocean surface wind speed and direction Scatterometer: 1,800 km swath, wind speed 3-20 m/s and 25 km wind vector resolution</td>
<td>GPS reflectometry constellation architecture for frequent revisits (e.g. CYGNSS)</td>
<td>Delay Doppler mapping instruments (GPS receivers)</td>
</tr>
<tr>
<td>HyspIRI</td>
<td>Surface composition &amp; ecosystem health VSWIR: 60m spatial resolution, 19-day revisit TIR: 60m spatial resolution, 5-day revisit</td>
<td>Separate spacecraft designed to SmallSat Pegasus configuration (e.g. Dyson-VSWIR)</td>
<td>Compact Dyson imaging spectrometer design</td>
</tr>
<tr>
<td>GPM</td>
<td>3D precipitation structure Ka-band (35.5 GHz) and Ku-band (13.6 GHz) precipitation radars at 125 km and 245 km swaths</td>
<td>Ka-band constellation alternative measurement approach (e.g. RainCube)</td>
<td>Ka-band deployable antenna and pulse compression method</td>
</tr>
<tr>
<td>PATH</td>
<td>All-weather temp/humidity soundings Spectrometric observations of microwave emission in 50-70, 118, 183 GHz lines</td>
<td>Radiometer and/or GPSRO constellation architecture (e.g. Mistic Winds / MiRaTA)</td>
<td>Compact MWIR design, radiometers, and GPS receivers</td>
</tr>
<tr>
<td>3D Winds</td>
<td>3D Tropospheric winds 2-micron and ultraviolet Doppler wind lidar</td>
<td>No immediate alternative</td>
<td>Laser SWaP and duty cycle capabilities must advance</td>
</tr>
</tbody>
</table>

Alternative approaches either provide an equivalent measurement, no clear alternative, or a reduced scope measurement that may satisfy specific requirements.
Correlates precipitation structure evolution, including diurnal cycle, to the evolution of the upper-level warm core and intensity changes.

Relates the occurrence of intense precipitation cores (convective bursts) to storm intensity evolution.

Relates retrieved environmental moisture measurements to coincident measures of storm structure.

**MicroMAS-2 CubeSat**

Each MicroMAS-2 CubeSat is a dual-spinning 3U CubeSat equipped with a 12-channel passive microwave spectrometer.

**Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of SmallSats (TROPICS)**

- **Launch Mass**: 3.6 kg (per each of 12 satellites)
- **Instrument**: Microwave spectrometer
- **Design**: 12 identical 3U CubeSats
- **Development to Launch**: 2016 - 2019
- **Manufacturers**: Massachusetts Institute of Technology
2015 Technology Highlights - Planetary Science

MarCO
Two 6U CubeSats, flying with the InSight mission to Mars, to act as real-time EDL telecom relays

LunaH-Map
6U CubeSat that will fly on the Earth-Moon 1 (EM1) to sense the presence of hydrogen in craters and dark shadows on the Moon

CubeSat Study Missions
Mars Micro Orbiter, Hydrogen Albedo Lunar Orbiter (HALO), Diminutive Asteroid Visitor using Ion Drive (DAVID)
## Joint SMD/STMD Study - Planetary Science

*Mission concepts for small satellites are needed*

Study requires additional mission concepts that involve small spacecraft
SMD is requesting input from the Assessment Groups to help define notional requirements for small spacecraft - the following survey is being provided to all of the AGs

<table>
<thead>
<tr>
<th>Science Application</th>
<th>Brief Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NASA Relevance</strong></td>
<td>Link science application to the SMD Decadal Survey science priorities, HEOMD (strategic knowledge gaps), Planetary Defense.</td>
</tr>
<tr>
<td><strong>Nature of Investigation</strong></td>
<td>Detail the type of measurement to be performed (in a few sentences).</td>
</tr>
<tr>
<td><strong>Targets</strong></td>
<td>List of planetary bodies at which the investigation is applicable or sought.</td>
</tr>
<tr>
<td><strong>Instrument</strong></td>
<td>Describe the type of instrument and performance sought for the investigation.</td>
</tr>
<tr>
<td><strong>Instrument Availability?</strong></td>
<td>Indicate if instrument already exists, under development (which program?), not available, or if availability is unknown.</td>
</tr>
<tr>
<td><strong>Type of Architecture and Vantage Point</strong></td>
<td>Indicate if the investigation is performed in situ or remote; precise if it is best accomplished in a mother-daughter architecture, constellations, or single (independent) asset.</td>
</tr>
<tr>
<td><strong>Novel/Unique Contribution</strong></td>
<td>Explain why CubeSats or SmallSats are uniquely placed to perform the proposed investigation.</td>
</tr>
<tr>
<td><strong>Challenges</strong></td>
<td>Detail challenges you are aware of (e.g., resources, attitude control, etc.) for implementing the investigation in a CubeSat/SmallSat.</td>
</tr>
</tbody>
</table>
CubeSat Concepts for Small Body Missions

Examples from SBAG small spacecraft survey

**Swarm Flyby Gravimetry**
Justin Atchison/Johns Hopkins University
NIAC 2015 Phase II

- Estimate an asteroid’s gravity field and infer its underlying composition and structure.
- 6U P-Pod sized simple probes ejected from an orbiter. Two types: diffusely reflective spheres tracked by telescope, and spherical corner-cube retro-reflectors tracked by lidar.
- IR tracking is limited by available on-board energy storage and the quality of infrared focal plane arrays, and RF beacons require low cost, ultra-stable oscillator circuits. Low cost/mass/volume/power consumption of spacecraft pointing technologies would be beneficial.

**Spacecraft/Rover Hybrids for the Exploration of Small Solar System Bodies**
Marco Pavone/Stanford
NIAC 2014 Phase II

- Systematic in-situ exploration.
- 8U-sized hybrid mobility platforms actuated by internal flywheels. Each carries an imaging camera, microscope, and APXS instrument. The platforms are scalable from 1U to 27U.
- The lifetime of the platforms is limited by the battery – improved primary battery capacity and/or lower power consumption instruments would extend the mission range.

**Seismic Exploration of Small Bodies**
Jeffrey Plescia/JHU
NIAC 2015 Phase I

- Understand the interior structure of small bodies.
- CubeSats deploy micro-seismometers on the surface. Each independently detonates to provide an energy source for the remaining others to detect.
- Active seismology experiment would provide the seismic velocity of the interior across some number of ray paths and thus resolve whether asteroids are rubble piles or have solid interiors with a fragmental surface layer.
New Solicitation: Planetary Science Deep Space SmallSat Studies

*Funding will be provided for formal mission design studies*

**Overview:** Approximately $3M to be made available to fund 6-15 6-month studies

**Goals:**
- Acquire detailed concept studies for deep space Planetary Science missions that can be accomplished with small spacecraft
- Stimulate creativity in the community for science enabled by small, low cost deep space missions ($10M - $100M) - proposals should push state of the art

Proposed investigations should be responsive to the goals of NASA’s Planetary Science Division

Official announcement will be made by the Planetary Science Division through ROSES (POC: William Cook)
Backups
Planetary Science

Missions in Formulation / Operating

Strategic Missions (Notional)
Current Findings and Observations

*Constellations, platform diversity, and dedicated launch*

For Earth observations, given instrument duty cycles, power requirements, data downlink needs, and reliability, most Decadal-like science (from SmallSats) may require flight systems larger than CubeSats likely in the 50 kg to ESPA-class regime or higher.

Constellation mission designs are a growing trend that will enable more frequent observations with greater coverage and the ability to support sustained continuity measurements at reasonable costs over time.

Dedicated launch capabilities that can support a variety of small satellite systems will need to continue to mature.

**Virgin Galactic Launcher One**
- **Launch Mass:** 225 kg (LEO) or 125 kg (SSO)
- **Accommodation:** ESPA-Class envelope
- **Cost:** Less than $10 million per flight
- **Manufacturers:** Virgin Galactic