National Aeronautics and
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A Comparison of the Technological Maturation of SmallSat Propulsion Systems from 2018 to 2020

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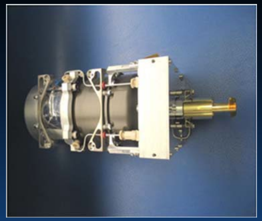
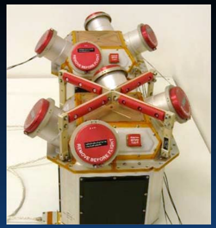
Introduction

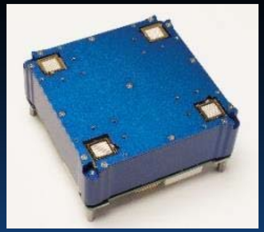
This paper identifies some of the advancements in SmallSat propulsion in the last two years that was captured in the Small Spacecraft Technology State-of-the-Art (SoA) report*, 2018 and 2020 editions

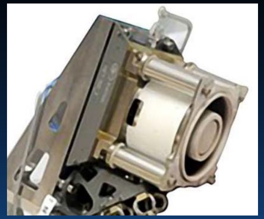
- A small spacecraft is <180 kg wet mass
- SoA is TRL 5 and higher
- SoA report work is managed by NASA's Small Spacecraft Systems Virtual Institute (S3VI) and performed by multiple contributors
- The S3VI is jointly funded by NASA's Space Technology Mission Directorate and Science Mission Directorate

Recent efforts have enhanced the capability of SmallSat propulsion since 2018

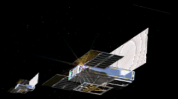
- 2019 NASA's Tipping Point solicitation selection (Accion, ExoTerra, CU Aerospace)
- NASA's Artemis I mission will deploy twelve propulsive 6U spacecraft





** Note: the SoA report does not represent an endorsement by NASA.*



SmallSat Propulsion

Perform orbital changes and maintenance (altitude and inclination), attitude control (pointing and desaturation of reaction wheels), drag compensation, and deorbiting

Two development paths:

- Systems and components with flight heritage are being reconsidered to meet the needs of smaller spacecraft
  - Minimizes new product development risk and time to market by creating devices similar to those with existing spaceflight heritage
  - Accounts for small spacecraft volume, mass, power, safety and cost considerations
- Novel technologies specifically for small spacecraft
  - Technologies that offer small spacecraft a level of propulsive capability not easily matched through the miniaturization of heritage technologies

2020 “In-Space Propulsion” Chapter Structure

- 2018 “Propulsion” chapter: list and describe publicly known smallsat propulsion systems
- 2020 “In-Space Propulsion” chapter: a deeper dive in the maturity assessment of each technology
  - Operational and integrational considerations for reader’s awareness
  - Distinguishes propulsion systems from propulsion components
  - Highlights notable missions of potential significance
  - Reorganized the data to improve overall comprehension on the subject
- Utilizes the **Progress towards Mission Infusion (PMI)** classification system to complement NASA’s TRL scale to assist in the down-select of an in-space propulsive device
  - Concept (TRL 1 – 3)
  - In-Development (TRL 4 – 5)
  - Engineering-to-Flight (TRL 5 – 6)
  - Flight-Demonstrated (TRL 7 – 9)

Progress towards Mission Infusion (PMI)

Concept, 'C'

- At minimum, an idea has been established as scientifically feasible.
- May even include experimental verification of the underlying physics.
- May even include notional device designs.
- Approximately aligns to NASA TRL 1-3

In-Development, 'D'

- At minimum, a low-fidelity device that has been operated in an appropriate environment to demonstrate the basic functionality and predict the ultimate capabilities.
- May even be a medium- or high-fidelity device operated in a simulated final environment, but the device lacks a specific mission pull to define requirements and a qualification program.
- May even be a medium- or high-fidelity device operated in a flight demonstration, but the device lacks sufficient fidelity or demonstrated capability to reflect the anticipated final product.
- Approximately aligns to NASA TRL 4-5

Engineering-to-Flight, 'E'

- At minimum, a medium-fidelity device that has been operated in a simulated final environment and demonstrates key capabilities relative to the requirements of a specific mission.
- May even include a qualification program in-progress or completed.
- May even include a spaceflight, but the device fails to demonstrate key capabilities.
- May even include a successful spaceflight, but the device is now being applied in a new environment or platform, necessitating a delta-qualification.
- A specific mission opportunity must be identified in open literature.
- Approximately aligns to NASA TRL 5-6

Flight-Demonstrated, 'F'

- At minimum, a high-fidelity component or system (fit, form, and function) that has been operated in the intended in-space environment (e.g., LEO, GEO, deep space) on an appropriate platform, where key capabilities have been successfully demonstrated.
- May even be a final product that has completed a mission (not strictly a technology demonstration).
- May even be a product in repeat production and routine use for a number of missions.
- A successful spaceflight must be identified and the outcome described in open literature.
- Approximately aligns to NASA TRL 7-9

SmallSat Propulsion Technology Maturity

Table 1: Comparison from 2018 and 2020 of Smallsat Propulsion that have now achieved PMI/Development Status ‘F’ (TRL 7-9)

Propulsion System Type	2018 status (TRL 5-6)	2020 status PMI F Status
GR-1 by Aerojet **Chemical**	Scheduled to launch 2018-2019 on Green Propulsion Infusion Mission a GR-1 thruster TRL 5-6	Launched five GR-1 thrusters summer 2019, operated successfully
Enpulsion Nano FEEP **Electrospray**	First space demonstration of thruster early 2018.	Several more smallsat demonstrations have been performed
Comet-1000 and -8000 by Bradford Space **Chemical (Water-based electrothermal)**	Both systems have expected launches for mid-late 2018.	Multiple successful launches of the Comet-8000 with BlackSky smallsats since late 2018 Multiple successful launches of the Comet-1000 on the HawkEye 360 3U clusters since late 2018 and five more clusters are expected to launch by mid-2022

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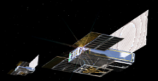

SmallSat Propulsion Technology Maturity

In-Development, 'D'

- At minimum, a low-fidelity device that has been operated in an appropriate environment to demonstrate the basic functionality and predict the ultimate capabilities.
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- May even be a medium- or high-fidelity device operated in a flight demonstration, but the device lacks sufficient fidelity or demonstrated capability to reflect the anticipated final product.
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Engineering-to-Flight, 'E'

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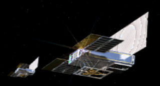
- A specific mission opportunity must be identified in open literature.
- Approximately aligns to NASA TRL 5-6

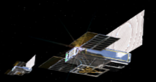
Table 2: Comparison of Smallsat Propulsion from 2018 to 2020 that have now achieved PMI/Development Status 'E' (TRL 5-6)

Propulsion System *Type*	2018 status (TRL 4 – 5)	2020 status PMI E Status
Micro CubeSat Propulsion System by VACCO ***Chemical***	Achieved 70,000 firings from endurance testing	Used on MarCO; Expected to launch in 2021 on CubeSat Proximity Operations Demonstration 3U spacecraft
All Artemis I 6U propulsion systems, *see Table 3*	Expected to launch late 2018	Expected to launch late 2021/early 2022
HYDROS-C by Tethers Unlimited ***Chemical***	Planned for launch early 2019	Launched Jan 2021 on PTD-1; mission complete in June 2021
TILE-2, -3 by Accion Systems ***Electric***	Has info on an obsolete product (TILE-5000)	TILE-2 is on-board 3U BeaverCube, launched June 2021 and awaiting deployment from ISS, and will be used in the Dual Propulsion Experiment (DUPLEX) 6U mission (2022 launch)



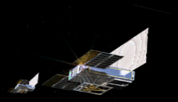
Artemis I Propulsive 6U Spacecraft

CubeSat Payloads ***Propulsion Type***	**Propulsion Payload**
TeamMiles *Electrical Prop*	Twelve ConstantQ iodine-propellant thrusters made by Miles Space to provide primary propulsion as well as 3-axis control
Cislunar Explorers *Chemical*	Water electrolysis system developed by Cornell University
Biosentinel *Chemical, Cold gas*	ACS cold gas propulsion system developed by Lightsey Space Research
Lunar Flashlight *Chemical, monopropellant*	Pump-fed system that has four 100-mN ASCENT thrusters
LunIR (SkyFire) *Electrospray*	Demonstrate electrospray propulsion to lower the spacecraft's orbit
CubeSat for Solar Particles (CuSP) *Chemical, Cold gas*	Micro-Propulsion System (MiPS) (VACCO Industries)



Artemis I Propulsive 6U Spacecraft

CubeSat Payloads ***Propulsion Type***	**Propulsion Payload**
NEA Scout *Propellant-less, solar sail & chemical, cold gas*	(Primary) 85 m^2 solar sail & (secondary for steering) VACCO cold gas MiPS
Lunar IceCube *Electric, Gridded Ion* Thruster	Busek BIT-3 propulsion system with solid iodine propellant
Lunar Polar Hydrogen Mapper (LunaH-Map) *Electric, Gridded Ion Thruster*	Busek BIT-3 propulsion system with solid iodine propellant
EQUULEUS *Chemical, warm-gas propulsion system*	AQUARIUS (AQUA ResIstojet propUlsion System) propulsion system consisting of eight water thrusters also used for attitude control and momentum management
OMTENASHI *Chemical*	Solid rocket motor slow the nano-lander as it descends to the Moon
ArgoMoon *Chemical, monopropellant*	Micro Propulsion System (MiPS) by VACCO



Thank you

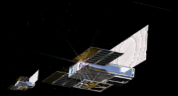
Visit the Small Spacecraft Systems Virtual Institute's Web portal to view entire SoA report online

https://www.nasa.gov/smallsat-institute/sst-soa-2020

Reach out to the Small Spacecraft Systems Virtual Institute for further comments and questions

agency-smallsat-institute@mail.nasa.gov

S3VI: www.nasa.gov/smallsat-institute



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