Overview of NASA's Science Mission Directorate Small Satellites programs and Advances in Transformative Science Measurements with Small Satellites

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ABSTRACT

Small satellites have become an accepted platform for enabling high-quality science measurements and observations. NASA missions have leveraged advances in sensor miniaturization, technology innovations, and new small satellite mission architectures to support high spatial and temporal measurements, continuity measurements, and constellations in response to science objectives described in NASA's Decadal Surveys.

Across six divisions of the Science Mission Directorate (SMD), over 12 years, SMD has funded 88 CubeSat / SmallSat Missions and 59 Studies to date. Currently, SMD has 53 small spacecraft science missions (87 spacecraft) in implementation or formulation.

This paper provides the background of efforts to promote the implementation of small satellites within NASA as a balanced portfolio for the agency's science, technology, and exploration goals. We include analysis of SmallSat awards and trends funded by SMD through Research Opportunities in Space and Earth Sciences (ROSES), Small Innovative Missions for Planetary Exploration (SIMPLEx), and Small Explorer (SMEX) and Medium Explorer (MIDEX) calls over the last 12 years. The data source of this assessment is a subset of the NASA SmallSat Coordination Group Database, a collection of all known funded NASA SmallSat and CubeSat missions and studies.

This paper also provides an overview of small satellite programs and selected missions from SMD's divisions: Astrophysics, Heliophysics, Earth Science, and Planetary Science, and describes SMD's efforts in fostering an incremental and continuous path to achieve high-priority science through transformative science measurements.

This paper recognizes the latest observations and trends of the NASA CubeSat / SmallSat Science missions with masses ranging between 1kg to 500kg.

1 The Promise of Small Satellites

NASA has embraced small satellites, from CubeSats to ESPA-class satellites, as another tool in its portfolio for high-value science missions. Small satellites are no longer disruptive but are flourishing and are fully accepted as part of NASA's science toolkit. In the past decade, NASA's Science Mission Directorate (SMD) has been selecting and flying many small satellites constellation missions to create high temporal and high spatial measurements for unique targeted science. At the same time, with its lower price points and shorter development cycles, NASA is leveraging CubeSats and SmallSats to prove out new technologies and train the next generation of engineers and scientists. Small satellites collect data that complement data from large satellites and in some cases, collect data that otherwise cannot be achieved by large satellites to contribute to our Science goals.

In response to the Decadal Surveys produced by the National Academies of Science, NASA has leveraged advances in sensor miniaturization, both homegrown and commercial , and new mission architectures to support high spatial and temporal measurements, continuity measurements, and constellations using small satellites across the Astrophysics, Heliophysics, Earth Science, and Planetary Science divisions.

Since 2010, SMD has funded 88 CubeSat / SmallSat Missions and 59 Studies across six divisions. Currently, SMD has 53 small spacecraft science missions (87 spacecraft) in implementation or formulation.

2 Definitions and Data Source

For the purposes of this analysis, a SmallSat is defined in the SMD handbook, as "*A spacecraft that is interface compatible with an ESPA Ring, a dedicated small or medium-lift launch vehicle, or a containerized dispenser, and with an upper mass limit of approximately 500 kg*."

Below are form factor configuration for CubeSats. Each 1U form factor measures 10 cm^3 and the mass of each U is approximately 1.3 kg.

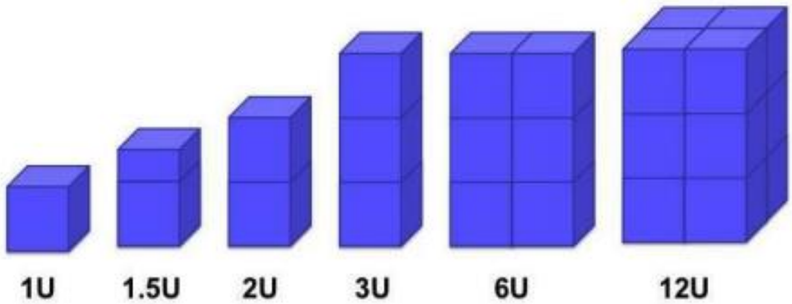

Figure 1 CubeSat Form Factors Source: NASA

A constellation mission is one that is defined by 2 or more spacecraft.

All data presented in this paper is from the period between 2010 to April 2022.

3 The Small Spacecraft Coordination Group (SSCG)

In response to recommendations from the National Academies of Science (NAS) "Achieving Science with CubeSats" report in 2017, NASA stood up the Small Spacecraft Coordination Group (SSCG).

The SSCG role encompasses matters related to small spacecraft and constellations of small spacecraft, from CubeSats to ESPA-Class. NASA recognized Small Satellites' role as a disruptive force in science space research and exploration. The SSCG was formed to provide a forum for central coordination of NASA small spacecraft missions with the objectives of recommending strategy, policy, and providing advice to the Agency Program Management Council (APMC) and the Associate Administrators of Science Mission Directorate (SMD), Space Technology Mission Directorate (STMD), and the Space Operations Mission Directorate (SOMD).

The SSCG is comprised of representatives from SMD, STMD, and SOMD, NASA offices, NASA centers, and the Jet Propulsion Laboratory (JPL). The SSCG chair traditionally originates from SMD and SMD also leads the SSCG among NASA Headquarters mission directorates and offices, and the

Small Spacecraft Working Group (SSWG) among SMD divisions (**Figure 2**).

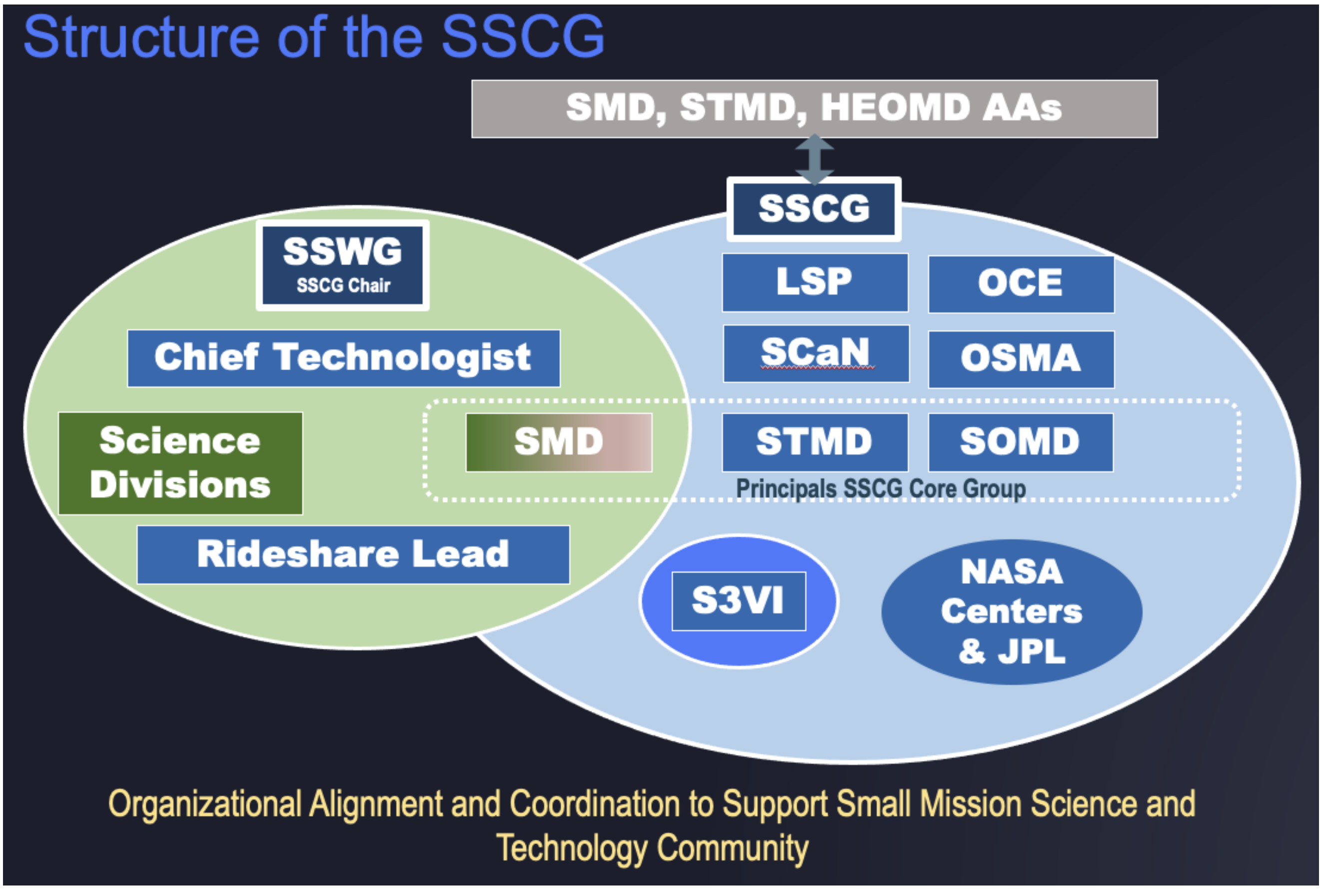

Figure 2 Small Spacecraft Coordination Group and Small Spacecraft Working Group Structure

In 2019, the SSCG released the Small Spacecraft Strategic Plan and identified four cross-cutting themes that are responsive to the Agencies' strategic goals utilizing Small Spacecraft: **High Priority Innovative Science, Support to Human Exploration, Disruptive Technology Innovation**, and **Regular Access to Space**. This plan formalizes the overarching integrated strategy common to the three mission directorates. The strategies were influenced by the NAS report recommendations and add guidance to those recommendations to account for the future capability and growth in launch systems secondary payload adapter (SPA)-class spacecraft.

The SSCG areas of focus include Strategy & Implementation, Launch Accommodation & Rideshare, Services & Infrastructure, Safety, Mission Assurance, and Reliability, Orbital Debris, CyberSecurity & Enterprise Protection, Commercial Partnerships & New Space, International Relationships and Outreach. SSCG coordinates and supports Small Space Missions in our Science and Technology communities across NASA centers and Jet Propulsion Laboratory.

4 SMD Small Satellites by the Numbers

SMD has funded 133 CubeSat and SmallSat Missions and Studies totaling USD $3 billion since 2010 across its six divisions. Spacecraft sizes 6U or larger comprise more than 60% awarded missions. Although the Earth Science Division (ESD) was the first division to fly CubeSats under its In-Space Validation of Earth Science Technology (INVEST) program, the Heliophysics Division (HPD) has funded the highest number SmallSat and CubeSat missions, whereas the Astrophysics Division (APD) has invested in the highest aggregate funding towards SmallSat and CubeSat missions among of all SMD divisions (**Figure 3 and Figure 4**).

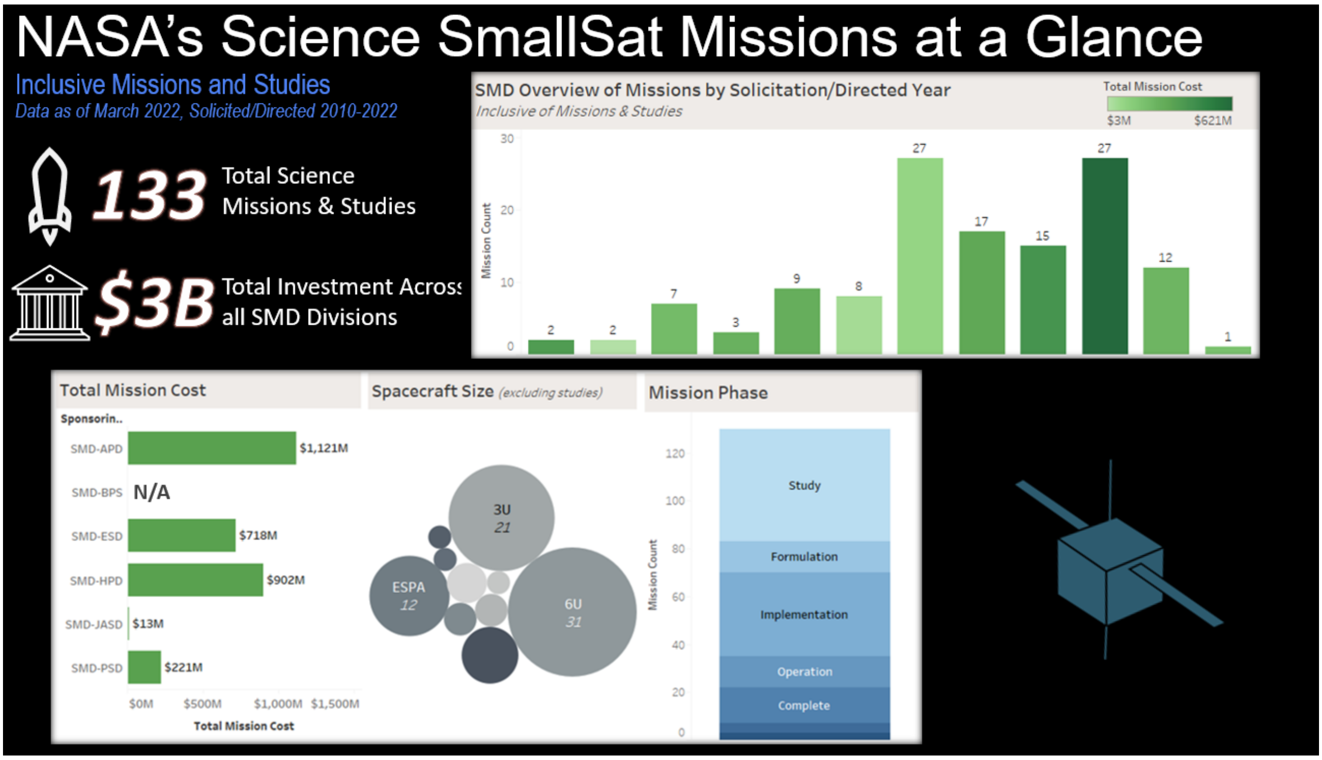

Figure 3 SMD SmallSat and CubeSat Missions a Glance

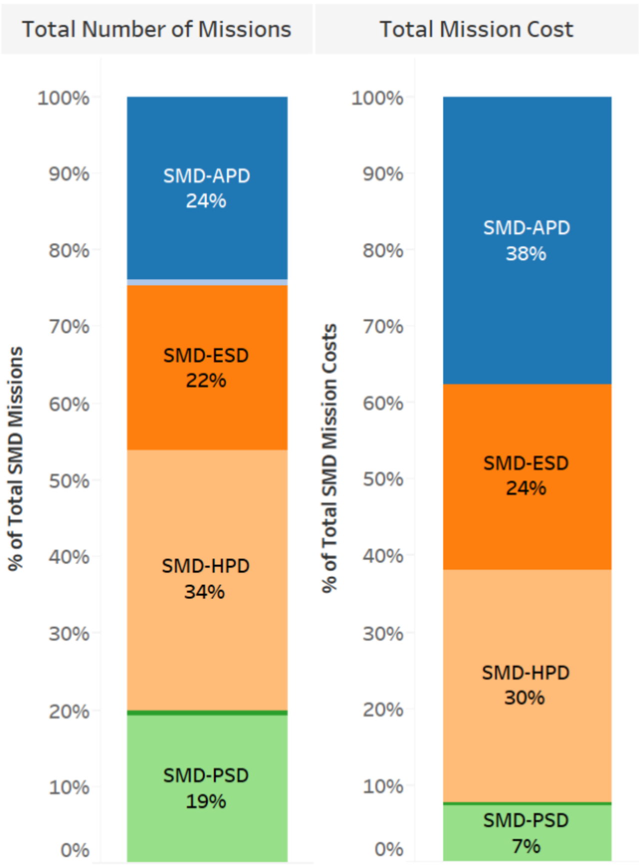

Figure 4 NASA Science SmallSat and CubeSat Missions and Studies Awards by Division

More than 80% of SMD-awarded small satellites support science and the rest of the awards are for the purpose of technology demonstration and maturation.

5 SMD Divisions SmallSat and CubeSat Programs

Each division within SMD has employed the use of CubeSats and SmallSats to accomplish high priority science objectives. In implementing the National Academy of Science's report on Advancing Science with Small Spacecraft, all divisions leveraged and partnered with the growing commercial sector for spacecraft components as well as access to space for their missions.

As previously discussed, Heliophysics (HPD) has embraced and advanced the use of small satellites for its science objectives. Its fleet of small satellites and CubeSats has experienced tremendous growth in the last five years. HPD's Flight Opportunities for Research and Technology (H-FORT) program has funded 10 CubeSat missions and studies in this period. In addition, HPD has funded 10 Small Satellite missions and studies under its Small Explorer, Solar Terrestrial Probes, and Mission of Opportunity programs. HPD has also selected the Helioswarm Constellation mission, a constellation of 1 large satellite and 8 small satellites, under its Medium Explorer or MIDEX programs (**Table 1**).

Astrophysics (APD) CubeSats are funded by the Astrophysics Research and Analysis (APRA) program and APD Small Satellites are funded by the PIONEERS Program, as well as the SMEX and MIDEX programs (**Table 1**).

The Earth Science Division's (ESD) In-Space Validation of Earth Science Technologies Program (INVEST) targets new technology, small instruments, and sensors to advance technology in relevant earth environment prior to use in a science mission. It has flown numerous CubeSats to validate and mature components and systems in the space environment.

In response to the recommendations of the Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond (The National Academies Press, 2007), ESD's Earth Venture (EV) program was established. EV has competitively selected science-driven low-cost SmallSat missions such as CYGNSS, TROPICS, PREFIRE, and INCUS, along with the technology demonstrator, TEMPEST-D, to add to our knowledge of current state of earth systems, and to improve predictions of future changes (**Table 1**).

The Planetary Science Division's (PSD) Small Innovative Missions for PLanetary Exploration (SIMPLEx) program supports the development of science investigations that require a spaceflight mission that can be accomplished using small spacecraft and has competitively selected the small satellites missions JANUS, Lunar Trailblazer, and ESCAPADE. Proposed investigations for SIMPLEx can target any body in the solar system except the Sun and Earth (**Table 1**).

Table 1 SMD SmallSat and CubeSat Programs

SMD Division or Office	Programs that fund CubeSats	Example CubeSat Missions	Programs that fund SmallSats	Example SmallSat Missions
Astrophysics	APRA	SPRITE, BLACKCAT, CUTE, BURSTCUBE, HaloSat	PIONEERS	Starburst, Aspera, PANDORA
Astrophysics			Explorer SMEX	IXPE
Astrophysics			Explorer MIDEX	SPHEREx
Earth Science	INVEST	ACMES, SNOOPI, HyTI, CTIM-FD, NACHOS, RainCube, RAVAN, CubeRRT	Earth Venture/SMEX	CYGNSS, TROPICS, PREFIRE, INCUS, TEMPEST-D
Heliophysics	H-FORT	GTOSAT, AEPEX, AERO/VISTA, CURIE, REAL, DAILI, LLITED, CUSP	SIMPLEX-2 /SMEX/MIDEX	ESCAPADE
Heliophysics	Explorer Mission of Opportunity	SunRISE, EZIE	Small Explorer (SMEX) Program	TRACERS, PUNCH
Heliophysics	MIDEX	CubeSat Constellations such as ARCS Phase A 2019 MIDEX	STP Science Mission of Opportunity	GLIDE
Heliophysics			STP Technology Mission of Opportunity	Solar Cruiser
Heliophysics			Medium Explorer (MIDEX) Program	Helioswarm
Planetary Science	SIMPLEX-1	Q-PACE, LunaH-Map	SIMPLEX-2	Janus
Exploration Science Strategy and Integration Office			SIMPLEX-2	Lunar Trailblazer

6 SMD Divisions SmallSat and CubeSat programs

SMD expects to launch 19 total small satellites in 2022, comprising of 26 spacecraft and over 29 missions in 2023 to 2026 comprising more than 51 spacecraft (**Figure 5**).

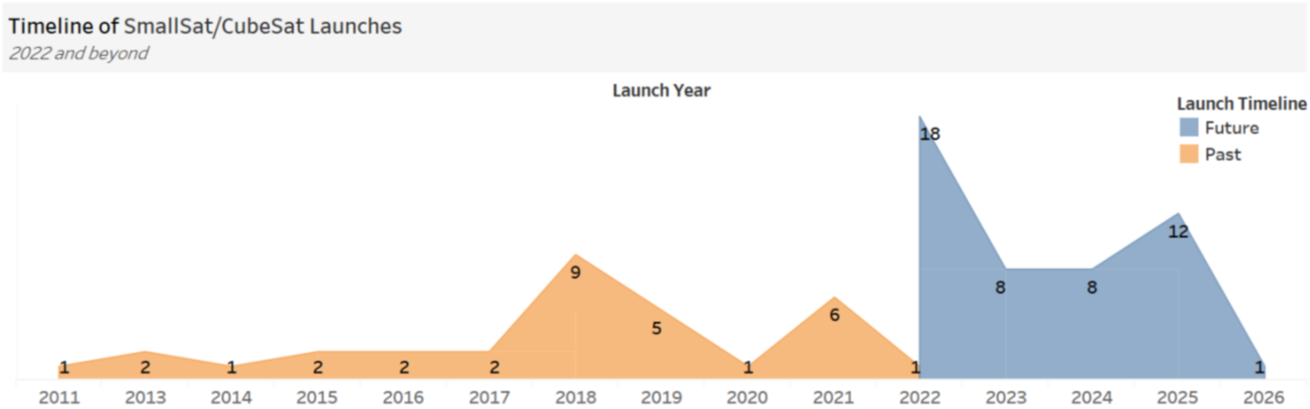

Figure 5 SMD SmallSat and CubeSat Launches er Year

Currently, NASA SMD has 53 small spacecraft science missions (87 spacecraft) in implementation or formulation. The full list of completed and future Science missions can be seen in the SmallSat/CubeSat Science Fleet Chart (**Figure 6**). The Fleet Chart depicts missions color coded by topic of study and Mission Directorate, with future missions notated in bold. Seventeen science missions have completed over the last 12 years, while four missions have resulted in failure.

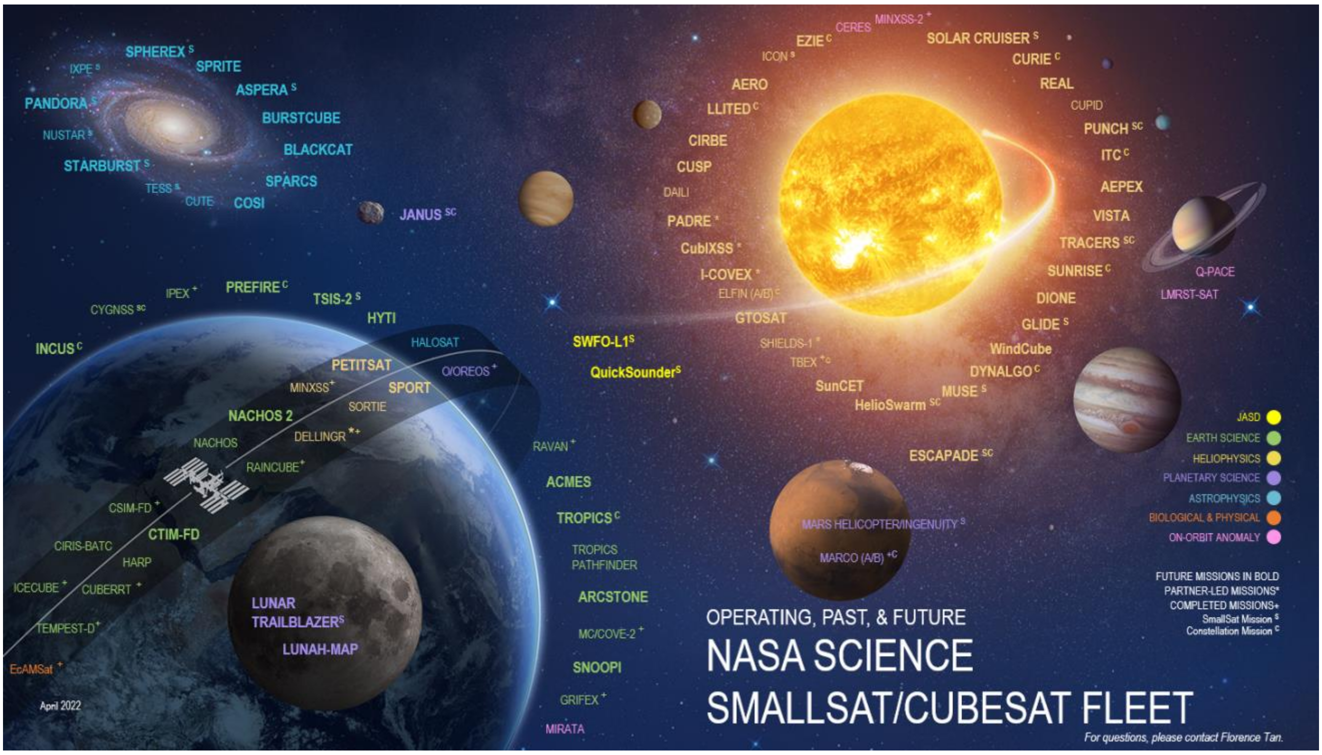

Figure 6 SmallSat/CubeSat Science Fleet

In addition, over the last 12 years, NASA's SmallSat missions has seen an increase in larger spacecraft and constellation missions. The missions are color coded with text colors to represent spacecraft sizes and multiple units. Notice that the missions on the right side of the line are missions that have launched; these missions are mostly white text depicting missions that are 3U and 6U form factor. The list of missions on the left of the vertical line are those in implementation and development and are more colorful – the blue text depicts ESPA class-missions, and the yellow text indicates missions with multiple spacecraft or constellations. Over the last decade, we have seen a shift towards larger small satellites and towards constellation missions (**Figure 7**).

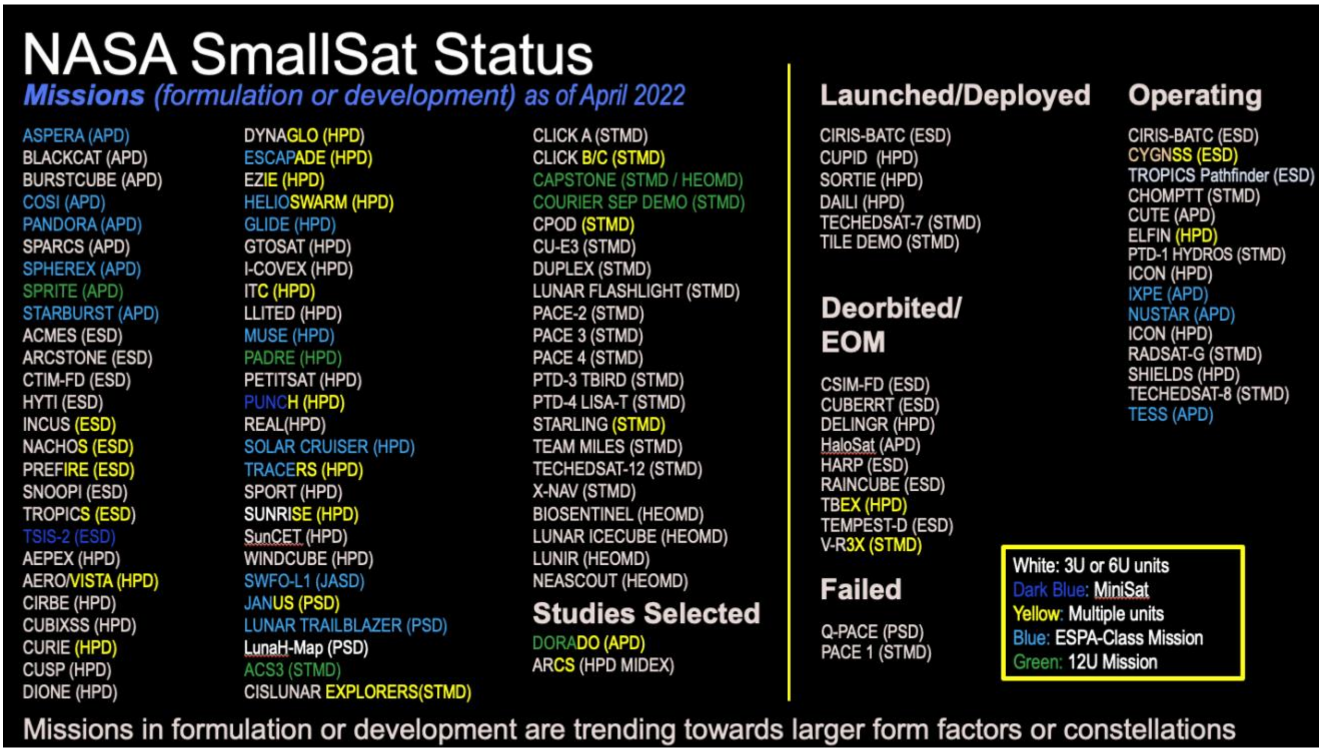

Figure 7 SMD SmallSat and CubeSat Missions Architecture Trends

7 Transformative Science with SmallSats

Six years ago, as SMD began launching more SmallSat and CubeSat missions, the associate administrator of NASA's Science Mission Directorate, Dr Thomas Zurbuchen, stated "NASA is increasingly using Small Satellites to tackle important science problems across our mission portfolio." Since then, NASA has begun to see the fruits of its missions.

In APD, the HaloSat CubeSat (**Figure 8)** mission was selected in 2015 to detect the missing matter in our universe by surveying soft X-ray emissions from the hot gas around our Milky Way. This effort led to five refereed papers in Astrophysical Journal and provided a set of data of soft X-ray emissions to advance our understanding of the Milky Way halo. HaloSat completed its mission in 2021.

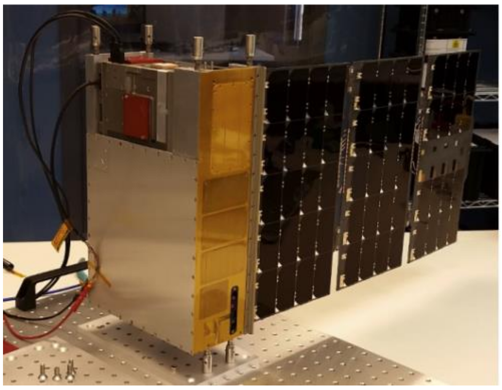

Figure 8 HaloSat CubeSat with Solar Panels deployed

The Cyclone, Global Navigation Satellite System (CYGNSS) mission was NASA's first Earth Science small satellite constellation mission and was originally proposed to measure wind intensity over the ocean to provide new insights into tropical cyclones by using reflections from GPS signals off the ocean surface to gain information of the properties of the surface. CYGNSS is led by Dr Chris Ruf at the University of Michigan, Ann Arbor. CYGNSS has not only succeeded in continuously measuring ocean surface winds in tropical storms, but also learned so much more information that can be revealed from measuring these GPS reflected signals from a constellation. Through CYGNSS, Dr Ruf and his team have uncovered new applications from the CYGNSS data from detecting the breeding ground for major locust outbreaks, to creating soil moisture maps over land, to imaging flood inundation before and after landfall of major hurricanes, and to producing a map of seasonal variation of microplastics in our global oceans (**Figure 9**).

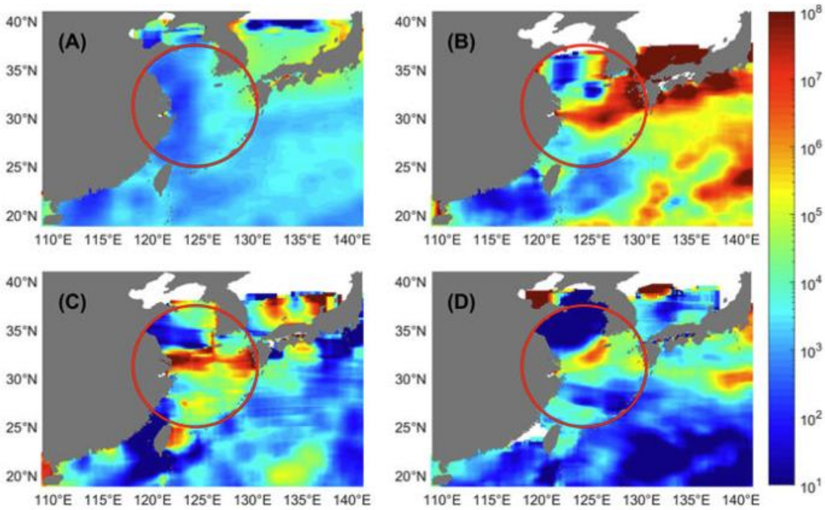

Figure 9 Microplastic concentration in the East China Sea averaged over different time intervals. (A) Annual average. One week averages over (B) 22–28 Jun 2017, (C) 27 Oct – 2 Nov 2017, (D) 2–8 Dec 2017. Short lived bursts of high microplastic concentration indicate river outflow. Source: *M. C. Evans and C. S. Ruf, "Toward the Detection and Imaging of Ocean Microplastics With a Spaceborne Radar," in* IEEE Transactions on Geoscience and Remote Sensing, *vol. 60, pp. 1-9, 2022, Art no. 4202709, doi:10.1109/TGRS.2021.3081691.*

With a constellation of small satellites such as INCUS, we seek to understand the formation of tropical convective storms and the conditions for extreme weather. With missions such as SunRISE, EZIE, TRACERS, and PUNCH, we are able to study the physics that drive the solar wind, solar flares, and coronal mass ejections, and with JANUS, we can study the formation and evolution of “rubble pile” asteroids.

8 Conclusions

NASA science has benefited from the use of small satellites as a unique and emerging platform for high-value science. NASA can leverage the growing commercial offerings in low size, weight, and power (SWaP) systems to construct missions at modest cost per spacecraft, to collect higher revisit-rate, simultaneous, large-scale space-based measurements, and to gain insight of global and space processes using Small Satellites. NASA’s fleet of past, operating, and future SmallSats and CubeSats – along with their big siblings – all contribute to provide transformative science data to increase our knowledge of our earth and space environments to inform our actions to protect and improve life on earth and in space and discover the secrets of the universe.

9 References

M. C. Evans and C. S. Ruf, "Toward the Detection and Imaging of Ocean Microplastics With a Spaceborne Radar," in IEEE Transactions on Geoscience and Remote Sensing, vol. 60, pp. 1-9, 2022, Art no. 4202709, doi:10.1109/TGRS.2021.3081691.

A. Zajczyk, P. Kaaret et al, "HaloSat: a search for missing baryons with a CubeSat," in 32nd Annual AIAA/USU Conference on Small Satellites, SSC18-WKIX-01