

A Review of Impending Small Satellite Formation Flying Missions

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Small satellites, like popular nanosatellite platforms called CubeSats, are suitable for formation flying missions because of their modular nature and low cost. This paper presents a review of thirty-nine missions, using multiple small satellites, in various stages of development. These missions are categorized based on their mission type, mission status, number of satellites, leading organization, funding source, and requirement for constellation or formation flying. We conclude that Earth science related missions are the most popular, while most multi-satellite missions only require a constellation. Although six missions aim to demonstrate formation flying capability in space using two to three small satellites, there are currently only two formation flying missions planning to use four or more small satellites.

I. Introduction

A formation flying (FF) mission involves a set of spatially distributed satellites, capable of autonomous interaction and cooperation with one another in order to maintain the desired formation.^{1,2} Small satellites are suitable for FF missions where a large number of satellites serve as distributed instruments for atmospheric sampling, construct a large distributed antenna platform, or make a large distributed aperture for imaging and other applications.³ Small satellites can be broadly classified into nanosatellites, which weigh between 1-10 kg; picosatellites, which weigh between 0.1-1 kg; and femtosatellites, which weigh less than 100 grams. CubeSats are a class of standardized nanosatellites, which range in sizes from 1U ($10 \times 10 \times 10$ cm) to 6U ($30 \times 20 \times 10$ cm), weigh between 1-8 kg, and are usually launched using the standardized CubeSat deployment system called Poly Picosatellite Orbital Deployer (P-POD).⁴ Due to their small size and modular nature, it is possible to launch multiple small satellites to accomplish a mission instead of a much bigger and costlier conventional satellite. In this paper, we survey thirty-nine multi-satellite missions in various stages of development, where each small satellite's mass is less than 30 kg, and categorize them based on their mission type, status, number of satellites, etc. The aim of this paper is to recognize state-of-the-art small satellite FF missions.

As shown in Fig. 1, the thirty-nine small satellite missions are grouped into five mission types, namely Earth science⁵ (Section II), astronomy and astrophysics⁶ (Section III), planetary science⁷ (Section IV), heliophysics⁸ (Section V), and technology demonstrations (Section VI). Multi-satellite missions are divided into two categories, namely FF and constellation missions. In FF missions, the dynamic states of the

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satellites are coupled through a common control law,^{9,10} i.e., at least one satellite must track a desired state relative to another satellite and the tracking control law must at the minimum depend upon the states of this other satellite. For example, even though specific relative positions are actively maintained, the Global Positioning System (GPS) satellites constitute a constellation since their orbit corrections only require an individual satellite's position and velocity (state).^{9,10} Fig. 1 shows the categorization of these missions based on the number of satellites and the requirement for formation flying or constellation. Based on the data presented in Fig. 1, we conclude that Earth science missions are the most popular (twenty missions) and most multi-satellite missions only require a constellation (twenty-four mission). Among the ten multi-satellite missions that actually require formation maintenance, six technology demonstration missions aim to demonstrate formation flying capability in space using two to three small satellites. Note that there are only two conceptual formation flying mission planning to use four or more small satellites.

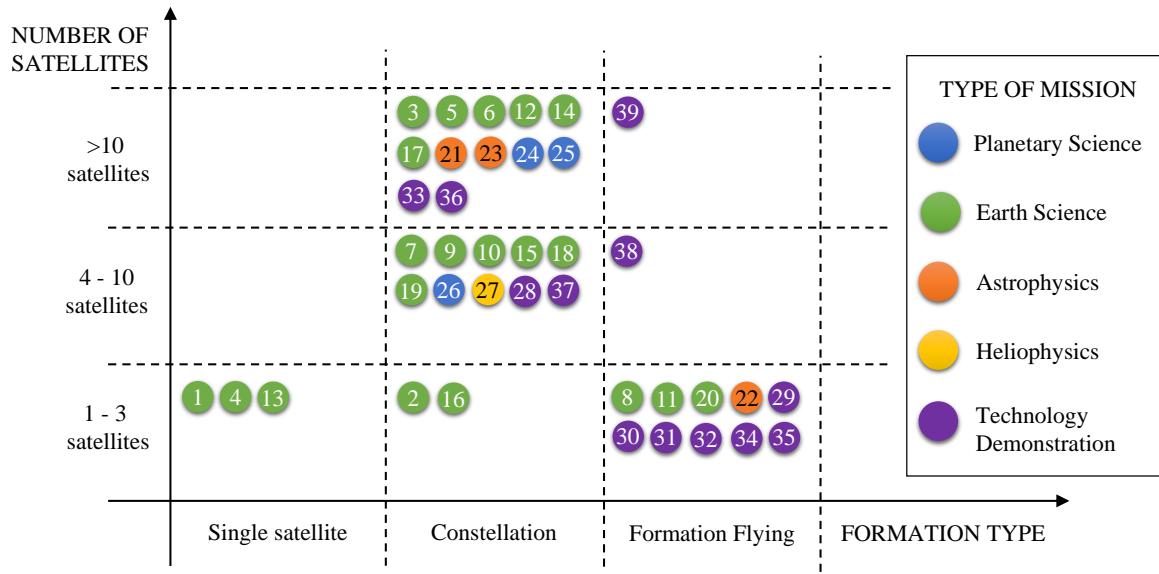


Figure 1: Categorization of thirty-nine multi-satellite missions based on their mission type, formation type and number of satellites. The key for these missions is given in Table 1.

The categorization of the thirty-nine multi-satellite missions based on their current mission status, organizations leading them and their funding sources are shown in Fig. 2. The main funding sources for multi-satellite missions are the National Aeronautics and Space Administration (NASA) and NASA centers like the Jet Propulsion Laboratory (JPL), the National Science Foundation (NSF), the Department of Defense (DoD), non-US agencies like the European Space Agency (ESA), Canadian Space Agency, Chinese Academy of Sciences, and private companies. The various mission status categories are: (i) concept, where the mission concept has been proposed and preliminary design work is being carried out; (ii) in development, where the hardware for the satellites is being developed; (iii) launch date set, where the launch date has been fixed or the mission has been selected for launch by NASA's Educational Launch of Nanosatellites (ELaNa) program;^{67,68} (iv) launched, where the mission has been recently launched and the satellites are currently in orbit around Earth; and (v) completed, where the satellites were previously launched and the mission successfully or unsuccessfully achieved its desired objectives. Based on the data presented Fig. 2, we conclude that most of these multi-satellite missions are led by universities around the world (twenty-two missions). Note that among eight FF technology demonstration missions, two have already been launched and two are set to launch shortly. The state-of-the-art technologies for small satellite FF missions are reviewed in Refs. 66, 69.

II. Earth Science Missions

The common aim of Earth science missions is “to develop a scientific understanding of the Earth system and its response to natural and human-induced changes to enable improved prediction of climate, weather, and natural hazards for present and future generations”.⁷⁰ A number of multi-satellite Earth science missions,

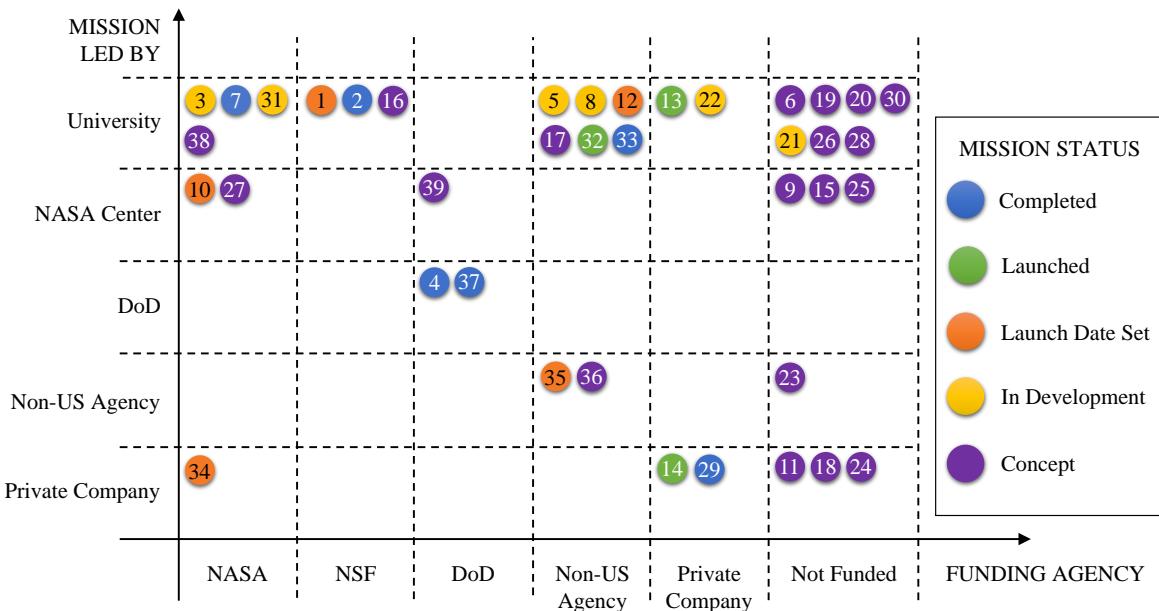


Figure 2: Categorization of thirty-nine multi-satellite missions based on their mission status, leading organization and funding source. The key for these missions is given in Table 1.

involving conventional large satellites, have been launched including the Afternoon Train (A-train),⁷¹ Gravity Recovery And Climate Experiment (GRACE),⁷² Time History of Events and Macroscale Interactions during Substorms (THEMIS),⁷³ Cluster II,⁷⁴ Swarm,⁷⁵ TerraSAR-X add-on for Digital Elevation Measurement (TanDEM-X)⁷⁶ and Skybox Imaging.⁷⁷

In this section, we present Earth science related missions which use or aim to use two or more small satellites whose weight range from 1 kg (CubeSat) to 30 kg. There are also a number of Earth science related missions which use only a single small satellite. For example, ionosphere monitoring is done by ExoCube,⁷⁸ Pratham,⁷⁹ weather monitoring is done by Weathernews Inc. Satellite (WNISAT),⁸⁰ the Colorado Student Space Weather Experiment (CSSWE).⁸¹ These single small satellite missions are not included in this study because this review focuses only on multi-satellite missions.

II.A. CubeSat investigating Atmospheric Density Response to Extreme driving (CADRE)

The CADRE project, led by University of Michigan and funded by NSF, aims to study the Earth's ionosphere and thermosphere for forecasting space weather events. The 3U CubeSat is equipped with the Wind Ion Neutral Composition Suite, which contains four electrostatic analyzers and two mass spectrometers, for measuring the in-situ density, temperature and composition of the thermosphere along with the neutral winds and ion flows. Recently CADRE was selected for launch into low Earth orbit (LEO) through NASA's ELaNa program. CADRE is a precursor mission for a constellation of CubeSats that will provide regional and global assessment of thermospheric features.¹¹

II.B. Dynamic Ionosphere CubeSat Experiment (DICE)

DICE was a multi-university mission, led by Utah State University and supported by NSF and NASA's ELaNa program, which launched two 1.5U CubeSats into an elliptical LEO (altitude of 820×410 km, inclination of 102°) in October 2011. As shown in Fig. 3(a), each identical satellite carried two Langmuir probes to measure ionospheric in-situ plasma densities, electric field probes to measure in situ DC and AC electric fields, and a magnetometer to measure in-situ DC and AC magnetic fields, which helped in accurate identification of geospace storm-time features like the geomagnetic-storm-enhanced density bulge and plume. In addition to successfully demonstrating a CubeSat constellation in space, the DICE mission also pushed the envelope of downlink communication data rate to 3 Mbits per second.^{12,13}

Table 1: Key for Fig. 1 and Fig. 2

Sr. No.	Name	Lead Institution	Section
1	CADRE ¹¹	University of Michigan	II.A
2	DICE ^{12, 13}	Utah State University	II.B
3	RocketCube ¹⁴	Dartmouth College	II.C
4	FalconSAT-2 ¹⁵	United States Air Force Academy	II.D
5	Charybdis ¹⁶	University of Strathclyde	II.E
6	ELF Measurement Project ¹⁷	Utah State University	II.F
7	OPAL ^{18, 19}	Stanford University	II.G
8	Drag-free CubeSat ^{20, 21}	University of Florida	II.H
9	Temperature and Humidity Sounding ²²	Jet Propulsion Laboratory, NASA	II.I
10	EDSN ^{23, 24, 25}	Ames Research Center, NASA	II.J
11	FTS CubeSat ²⁶	Exelis Geospatial Systems	II.K
12	QB50 ^{27, 28, 29}	Von Karman Institute	II.L
13	MicroMAS ^{30, 31}	Massachusetts Institute of Technology	II.M
14	Flock-1 ³²	Planet Labs	II.N
15	GGC ³³	Jet Propulsion Laboratory, NASA	II.O
16	FIREBIRD ^{34, 35}	Montana State University	II.P
17	Centinel ³⁶	Imperial College London	II.Q
18	Ionospheric Tomography ³⁷	SRI International	II.R
19	SSAsat ³⁸	University of Adelaide	II.S
20	InSAR ³⁹	University of Toronto	II.T
21	OLFAR ^{40, 41}	Delft University of Technology	III.A
22	AAReST ^{42, 43}	California Institute of Technology	III.B
23	SULFRO ⁴⁴	Chinese Academy of Science	III.C
24	Artemis ⁴⁵	Artemis Space	IV.A
25	CubeSat Constellation at Mars ⁴⁶	Jet Propulsion Laboratory, NASA	IV.B
26	iROCC ⁴⁷	Massachusetts Institute of Technology	IV.C
27	Solar Polar Imager ⁴⁸	Jet Propulsion Laboratory, NASA	V.A
28	HiMARC ^{49, 50}	Stanford University	VI.A
29	AeroCube-4 ^{51, 52}	Aerospace Corporation	VI.B
30	Real-Time Geolocation ⁵³	Israel Institute of Technology	VI.C
31	QUEST ⁵⁴	Kyushu University	VI.D
32	CanX-4&5 ^{55, 56}	University of Toronto	VI.E
33	KickSat ^{57, 58}	Cornell University	VI.F
34	CPOD ^{59, 60}	Tyvak Nano-Satellite Systems	VI.G
35	TW-1 ⁶¹	Chinese Academy of Science	VI.H
36	HumSat ^{62, 63}	European Space Agency	VI.I
37	Prometheus ^{64, 65}	Los Alamos National Laboratory	VI.J
38	UIUC-JPL FF Mission ⁶⁶	University of Illinois at Urbana-Champaign	VI.K
39	SWIFT ³	Jet Propulsion Laboratory, NASA	VI.L

II.C. RocketCube

The team from Dartmouth College is developing a suborbital CubeSat called RocketCube, which can be launched by a sounding rocket, to enable low-cost multipoint measurements for orbital and sub-orbital

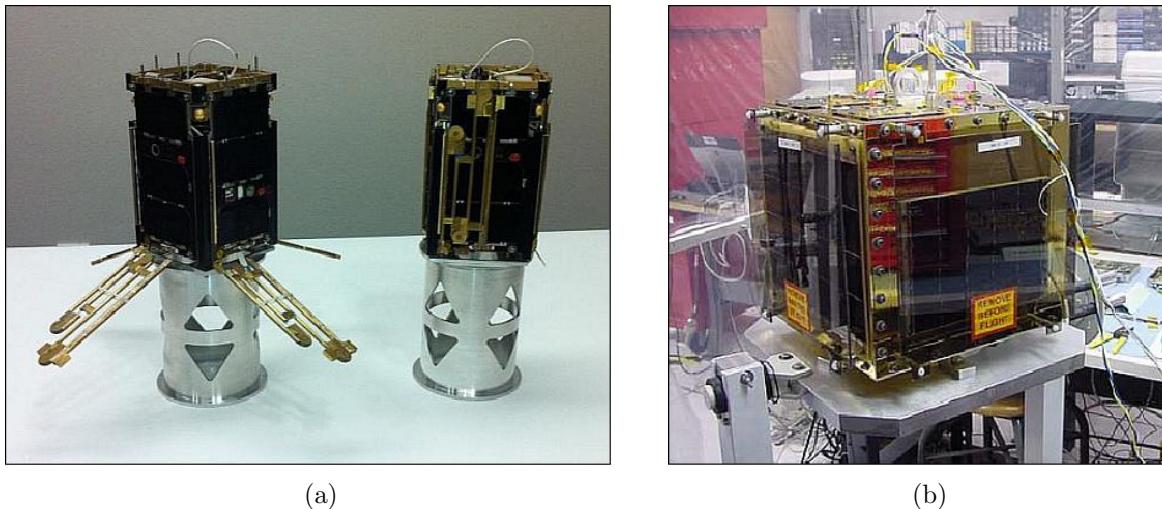


Figure 3: (a) Two DICE 1.5U nanosatellites prior to launch (image credit: Space Dynamics Laboratory, Utah State University⁸²). (b) FalconSat-2 in the USAFA clean room (image credit: USAFA⁸³).

scientific missions. The aim is to launch ten to twelve RocketCubes to observe the spatial and temporal variations in the ionosphere and aurora by conducting in situ observations.¹⁴ This mission is funded by JPL and NASA's Experimental Program to Stimulate Competitive Research (EPSCoR) program.

II.D. FalconSAT-2

The FalconSAT project is the United States Air Force Academy's (USAFA) small satellite engineering program. The FalconSAT-2 satellite, which weighed 20 kg as shown in Fig. 3(b), aimed to conduct multipoint in-situ measurements of ionospheric plasma depletions simultaneously with other satellites. The satellite was unsuccessfully launched by SpaceX's Falcon1 carrier rocket on March 24, 2006.¹⁵

II.E. Charybdis

The aim of the Charybdis constellation project, led by the University of Strathclyde and funded by the Engineering and Physical Sciences Research Council, UK; is to obtain high spatial, high temporal resolution multi-spectral images of coastal and inland waterways. This information is necessary for understanding the evolution of ecological systems and sediment suspension in river estuaries, the effects of anthropogenic processes on water systems, and the effects of tidal forcing on ocean color. The project aims to launch a constellation of 115 nanosatellites for bi-hourly global coverage or thirty nanosatellites for bi-hourly regional coverage over the UK mainland.¹⁶

II.F. Electrical Field (ELF) Measurement Project

The Electrical Field (ELF) measurement project concept, led by Utah State University, aimed to launch a constellation of forty eight satellites for setting up a global electrical field sensing system. Each microsatellite, would weigh less than 25 kg and incorporate a deployable sensor array (5 m boom) into a spinning oblate platform.¹⁷ Note that ESA's Swarm mission aims to measure the Earth's magnetic field with unprecedented accuracy using a constellation of three 500-kg satellites.⁸⁴

II.G. Orbiting Picosatellite Automatic Launcher (OPAL)

The OPAL mission, led by Stanford University and funded by JPL, successfully tested the feasibility of ejecting several picosatellites from a single larger microsatellite, which weighed 25.5 kg as shown in Fig. 4(a), in order to simultaneously sample a volume of space to study the magnetosphere's finer texture and dynamic nature.¹⁸ Each of the six picosatellites carried a small, two axis, fluxgate magnetometer, several photo detectors for spin rate detection, a micro processor and a high frequency transmitter.¹⁹ OPAL was

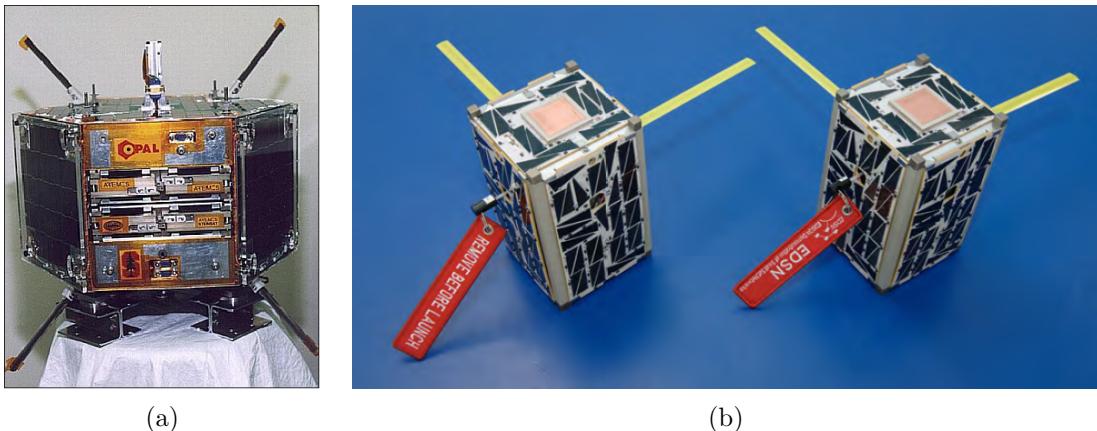


Figure 4: (a) Photograph of the OPAL microsatellite (image credit: Space Systems Development Laboratory, Stanford University¹⁸). (b) Photograph of two EDSN satellites (image credit: NASA Ames Research Center⁸⁵).

launched into a sun-synchronous near-circular LEO (altitude of 750 km, inclination of 97.5°, nodal crossing at 6AM/6 PM) as a secondary payload on an Orbital Sciences Corporation's Minotaur launch vehicle in January 27, 2000 from Vandenberg Air Force Base, CA. Note that ESA's Cluster II mission, which is composed of four identical 1.2-ton satellites flying in a tetrahedral formation, is studying the Earth's magnetosphere over the course of an entire solar cycle.⁷⁴

II.H. Drag-free CubeSat

The drag-free nanosatellite constellation concept, led by the University of Florida and Stanford University and primarily funded by King Abdulaziz City for Science and Technology, Saudi Arabia; aims to improve the sensitivity and spatial and temporal resolution of Earth aeronomy and geodesy measurements for accurately mapping the static and time-varying components of Earth's mass distribution.²⁰ Each CubeSat carries a precision small-scale drag-free gravitational reference sensor.²¹ Note that NASA's GRACE mission, which consists of two identical 500-kg satellites flying in a polar orbit about 220 km apart, has been making detailed measurements of the Earth's gravity field since March 2002.⁸⁶

II.I. Temperature and Humidity Sounding

The 6U CubeSat constellation concept for atmospheric temperature and humidity sounding, led by JPL, aims at launching four to fifteen low inclination satellites to image the key geophysical parameters that are needed to improve prediction of extreme weather events. Each 6U CubeSat will carry the 118 GHz temperature sounder instrument and the 183 GHz humidity sounder instrument.²² A similar concept for measuring the bidirectional reflectance distribution function of the Earth's surface, i.e., the directional and spectral variation of reflectance of the surface, using a constellation of nanosatellites has been proposed for precise determination of albedo.⁸⁷

II.J. Edison Demonstration of Smallsat Networks (EDSN)

The primary scientific purpose of the EDSN mission, led by NASA's Ames Research Center and funded by NASA's Space Technology Mission Directorate, is to demonstrate the capability of launching and deploying a fleet of eight CubeSats into a loose formation approximately 500 km above Earth. Each of the eight EDSN satellites in the constellation carries the Energetic Particle Integrating Space Environment Monitor payload in order to characterize the radiation environment in LEO by measuring the location and intensity of energetic charged particles simultaneously over a geographically dispersed area.^{23,24} The EDSN satellites, shown in Fig. 4(b), are to be launched into sun-synchronous LEO (altitude of 400 km) as secondary payloads on a Super-Strypi launch vehicle from Kauai, HI in January 2015.²⁵

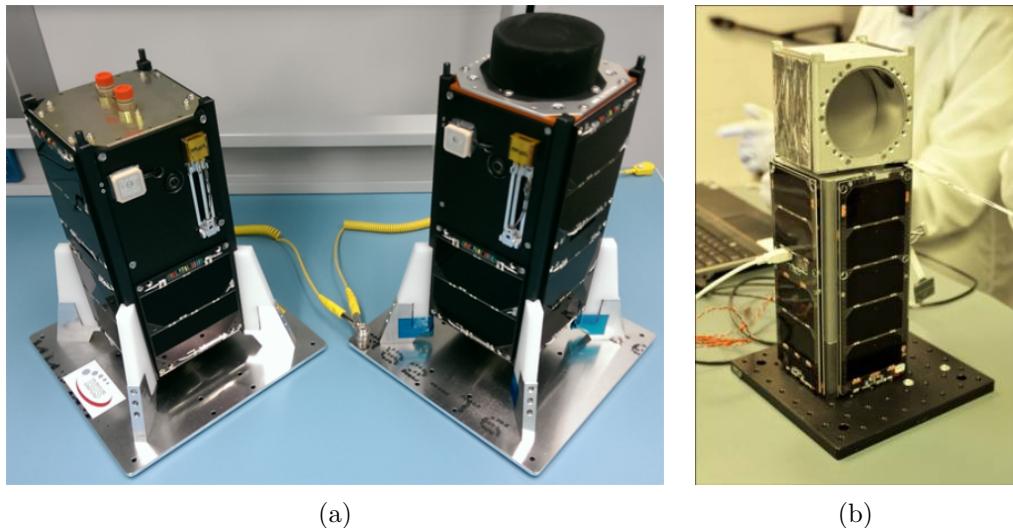


Figure 5: (a) The first two QB50 satellites ready for launch (image credit: Innovative Solutions In Space⁸⁸). (b) The MicroMAS nanosatellite in the MIT clean room (image credit: MIT Lincoln Laboratory⁸⁹).

II.K. Fourier Transform Spectrometer (FTS) CubeSat

In this conceptual design, led by Exelis Geospatial Systems and the University of Michigan, three formation flying 6U CubeSats, carrying the FTS payload, would cooperatively measure the global wind field for compiling vertical profiles of the wind field and for long-term weather forecasts.²⁶

II.L. QB50

The QB50 project, is a multi-university mission led by Von Karman Institute, Belgium and partially funded by the Research Executive Agency of the European Commission; aims to launch a network of fifty CubeSats, built by university-led teams all over the world, in order to perform multipoint, in situ measurements in the lower thermosphere (90 – 350 km) and re-entry research. Each 2U CubeSat carries a set of standardized sensors for lower thermosphere and re-entry research in addition to standard instruments for providing the usual satellite functions, as shown in Fig. 5(a). The project is scheduled for launch in mid-2015.^{27,28,29}

II.M. Microsized Microwave Atmospheric Satellite (MicroMAS)

The MicroMAS project, led by Massachusetts Institute of Technology (MIT) and funded by MIT Lincoln Laboratory, is a 3U CubeSat with a 1U passive spinning microwave spectrometer as shown in Fig. 5(b).⁹⁰ The project aims to create a constellation of small satellites with microwave radiometers to image hurricanes and tropical storms with improved temporal revisit over current systems.³⁰ The MicroMAS nanosatellite was launched into a near-circular LEO (altitude of 350 to 400 km, inclination of 51.6°) as a secondary cargo payload on an Orbital Sciences Corporation's Antares-120 launch vehicle in July 13, 2014 from Wallops Island, VA.³¹

II.N. Flock-1

The Flock-1 constellation, developed by Planet Labs Inc., consists of twenty-eight 3U CubeSats that will provide 3-5 m resolution images of Earth for environmental, humanitarian, and business applications. The Flock 1 CubeSats, shown in Fig. 6(a), were launched into LEO (altitude of 400 km, inclination of 52°) from the International Space Station using the NanoRacks CubeSat Deployer in mid-February 2014.³²

II.O. GNSS Geospace Constellation (GGC)

The GGC mission, led by JPL, is a space weather mission concept that proposes to use a CubeSat constellation with miniaturized GPS receivers for ionospheric remote sensing.³³ Here GNSS refers to the global

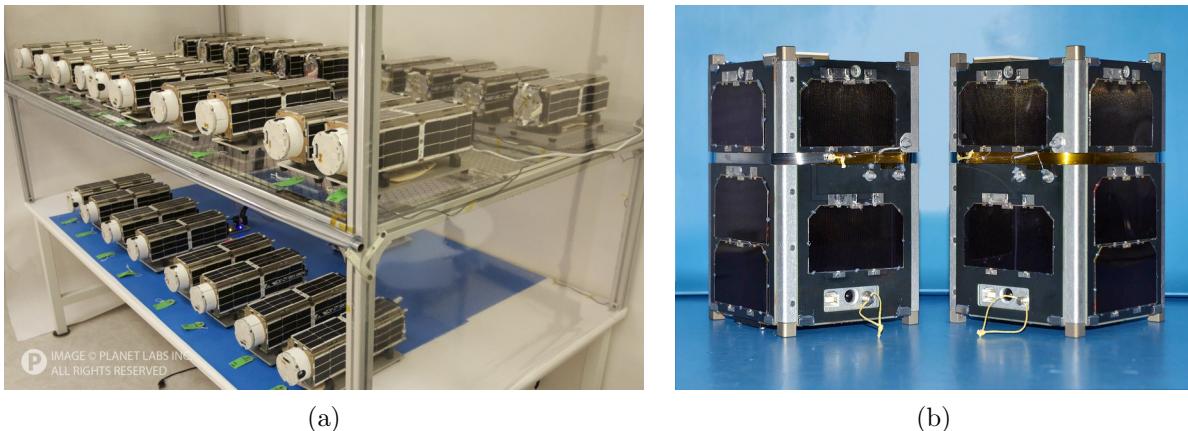


Figure 6: (a) Flock-1 nanosatellites prior to launch (image credit: Planet Labs³²). (b) FIREBIRD CubeSats prior to launch (image credit: University of New Hampshire⁹¹).

navigation satellite system.

II.P. Focused Investigations of Relativistic Electron Burst Intensity, Range, and Dynamics (FIREBIRD)

The FIREBIRD mission, led by Montana State University and the University of New Hampshire and funded by NSF, aimed to assess the spatial scale and spatial temporal ambiguity of magnetospheric microbursts in the Van Allen radiation belts using two 1.5U CubeSats. The two FIREBIRD CubeSats, shown in Fig. 6(b), were launched into sun-synchronous LEO (altitude of 467×883 km, inclination of 120.5°) as secondary payloads on an Atlas-5-501 vehicle from Vandenberg Air Force Base, CA in Dec. 6, 2013.^{34,35}

II.Q. Sentinel

The Sentinel mission concept, led by Imperial College London and funded by UK Space Agency, aims to launch a constellation of more than 100 CubeSats to study the magnetosphere. The satellites will perform in situ measurements to understand geomagnetic storm generation in the magnetosphere, especially in the magnetotail region where these storms start.³⁶

II.R. Ionospheric Tomography

This conceptual mission, led by SRI International, aims to use a constellation of CubeSats with digital television (DTV) receivers for ionospheric tomography. Each satellite will establish links with DTV stations and measure the phase variations of the DTV signals, to understand the ionospheric response to solar, magnetospheric and upper atmospheric forcing; and perform tomographic measurements of ionospheric density.³⁷

II.S. Space Situational Awareness (SSAsat)

The SSAsat conceptual mission, led by the University of Adelaide, Australia, aims to launch a small evenly-distributed constellation of five CubeSats to search for space debris in the medium Earth orbit and geostationary Earth orbit (GEO) belts.³⁸ A similar space situational awareness mission, where the CubeSat constellation is launched to 500 km above GEO, has also been proposed by the Lockheed Martin Space Systems.⁹²

II.T. Interferometric Synthetic Aperture Radar (InSAR)

The multistatic InSAR payload is being developed by the University of Toronto so that a formation flying mission could use sub-centimeter inter-satellite baseline knowledge for interferometric measurements. It is envisaged that this multistatic InSAR payload will be used for studying surface deformation, digital terrain

modeling, and moving target detection, where the formation will maintain the cartwheel and cross-track pendulum configurations.³⁹

III. Astronomy and Astrophysics Missions

The aim of astronomy and astrophysics missions is “to understand the universe and our place in it”⁹³. NASA’s Terrestrial Planet Finder (TPF) mission proposed to construct a system of four highly sensitive telescopes for detecting extrasolar terrestrial planets. A single CubeSat mission was proposed for performing observations in the 21cm wavelength from the shielded zone behind the Moon.⁴⁸ In this section, we present astronomy and astrophysics related missions which use or aim to use two or more small satellites.

III.A. Orbiting Low Frequency Antennas for Radio Astronomy (OLFAR)

The OLFAR mission concept, led by Delft University of Technology, is to deploy a swarm of 50-1000 identical nanosatellites for radio astronomy in the operational band of 0.3 – 30 MHz. Due to the opaqueness of the ionosphere to low frequency radio waves, the frequency band below 30 MHz is one of the last unexplored frequency range in radio astronomy. Each satellite will host an astronomical antenna of 5.0 m size, which will consist of three orthogonal dipoles.^{40, 41}

III.B. Autonomous Assembly of a Reconfigurable Space Telescope (AReST)

The AReST mission, led by California Institute of Technology and Surrey Space Centre and funded by Keck Institute for Space Studies, aims to demonstrate autonomous assembly and reconfiguration of a space telescope by having two 3U CubeSats autonomously un-dock and re-dock with a central 9U nanosatellite core. The central nanosatellite houses two fixed mirrors and a boom-deployed focal plane assembly, while the two 3U CubeSats each carry an electrically actuated adaptive mirror.^{42, 43}

III.C. Space Ultra-Low Frequency Radio Observatory (SULFRO)

The SULFRO mission concept, led by Chinese Academy of Science, aims to launch a constellation, consisting of a microsatellite mothership and twelve nanosatellite deputies, in a Lissajous or Halo orbit around the second Sun-Earth Lagrange point (L2), in a passive formation flying mode. Each deputy satellite will have three dipole antennas that will enable observing ‘all the sky all the time’ in the 1-100 MHz frequency range.⁴⁴

A summary of various astronomy and astrophysics related mission concepts that are possible using nanosatellites and the scientific and technological requirements for those missions are presented in Refs. 94, 95, 96. The requirements on position and attitude knowledge for state-of-the-art science missions are discussed in Ref. 97.

IV. Planetary Science Missions

The aim of planetary science missions is to understand the planets and small bodies that inhabit our solar system and the origins of life.⁹⁸ For example NASA’s GRAIL mission, which used two 200 kg spacecraft at 175-225 km separation, obtained high-quality gravitational field maps of the Moon in order to determine its interior structure.⁹⁹ Asteroid mapping and retrieval using a single 6U CubeSat has been proposed.^{100, 48} Here we present some planetary science related missions that need two or more small satellites.

IV.A. Artemis

The Artemis Earth mission concept, led by Artemis Space, is to launch a constellation of 200 nanosatellites that will be used for Earth observations and monitoring Earth’s local space environment. Artemis Space is also developing a lunar constellation of thirty-five small satellites and CubeSats which will provide a range of services, like providing telecommunications links, mapping of the Lunar surface, and support future missions on the Moon.⁴⁵

IV.B. CubeSat Constellation at Mars

The aim of this mission concept, led by JPL, is to launch a constellation of sixty CubeSats around Mars to study the frequency, geographical distribution and severity of electrical activity on Mars. It is envisaged that these orbiting sensors would be many orders of magnitude more sensitive than Earth-based sensors, even with less capable instruments onboard, due to their proximity to Mars.⁴⁶

IV.C. Interplanetary Radio Occultation CubeSat Constellation (iROCC)

The iROCC mission concept, led by MIT, aims to send six 3U CubeSats as a secondary payload on a larger interplanetary spacecraft to another planet. The constellation will use radio occultation to measure the temperature, pressure, and electron density profiles of a planet's atmosphere and ionosphere.⁴⁷

V. Heliophysics Missions

The aim of heliophysics missions is “to explore the Sun-Earth system to understand the Sun and its interactions with Earth and the solar system”.¹⁰¹ In this section, we present a heliophysics related mission that aims to use multiple small satellites.

V.A. Solar Polar Imager

This conceptual mission, led by JPL and funded by NASA's Innovative Advanced Concepts (NIAC), proposes to launch a constellation of six 6U CubeSats for studying helioseismology and magnetic fields of polar regions. The constellation will be placed in a highly inclined out-of-ecliptic vertical orbit with semimajor axis of approximately 0.99 astronomical unit. The CubeSats, equipped with host of scientific instruments, will use solar sails to reach the high inclination.⁴⁸

VI. Technology Demonstrations

Technology demonstration missions aim to demonstrate the application of state-of-the-art technology in space. Multi-satellite technology demonstration missions, using conventional large satellites, have been proposed like Technology Satellite of the 21st Century (TechSat-21),¹⁰² System F6,¹⁰³ and Project for On-Board Autonomy-3 (PROBA-3).¹⁰⁴ In this section, we present technology demonstration missions which use or aim to use two or more small satellites.

VI.A. High-speed, Multispectral, Adaptive Resolution Stereographic CubeSat Imaging Constellation (HiMARC)

The HiMARC mission concept, led by Stanford University, aims to launch four 3U synthetic aperture optical telescopes for providing rapid, multispectral, high-resolution stereographic images of terrestrial, solar, lunar, and astronomical targets.^{49,50}

VI.B. AeroCube-4

Three AeroCube-4 satellites were built by the Aerospace Corporation, where each 1U CubeSat weighed 1.2 kg as shown in Fig. 7(a). Each of these satellites was able to estimate its position with 20 m accuracy using a GPS receiver and could vary its cross-sectional area using extendable wings. The satellites were launched into elliptical LEO (altitude of 780×480 km, inclination of 65°) as secondary payloads on an Atlas-5-411 vehicle of United Launch Alliance from Vandenberg Air Force Base, CA in September 13, 2012.⁵¹ The satellites demonstrated formation flight by deliberately changing their drag profile, using different wing configurations, and reordered themselves over the course of several weeks.⁵²

VI.C. Real-Time Geolocation

This conceptual project, led by Israel Institute of Technology, aims to use a formation of two or three LEO satellites for performing measurements of sequential time difference of arrival in order to accurately determine the position of a terrestrial source emitting electromagnetic pulses. It is envisaged that space-borne

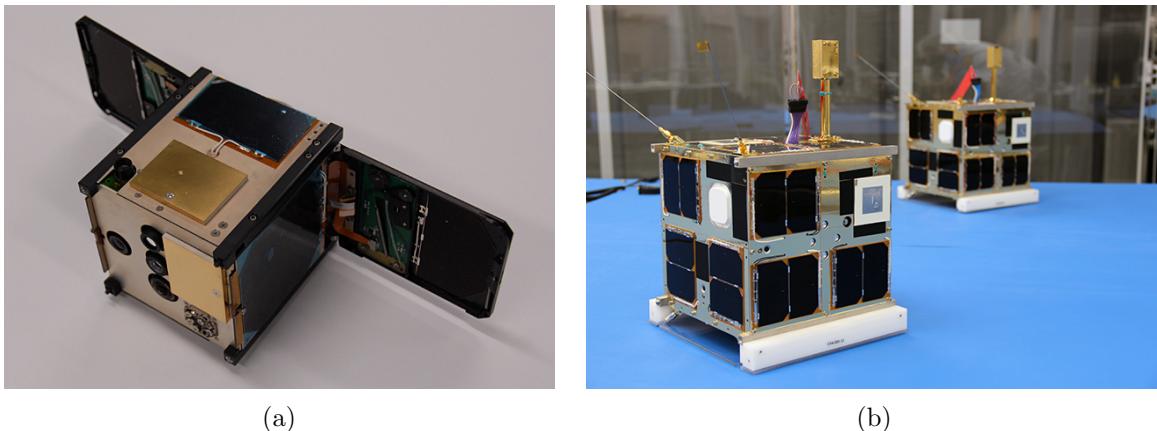


Figure 7: (a) Photograph of a deployed AeroCube-4 CubeSat (image credit: The Aerospace Corporation¹⁰⁵). (b) Photograph of the CanX-4 & 5 nanosatellites (image credit: Space Flight Laboratory, University of Toronto Institute for Aerospace Studies¹⁰⁶).

geolocation with a small satellite formation could provide accurate tracking of a Mars rover, a redundant navigation system in a jammed GNSS environment, or a cost-effective system for autonomously locating distress signals.⁵³

VI.D. Kyushu/US Experimental Satellite Tether (QUEST)

The QUEST mission, which is a joint project between Arizona State University, Santa Clara University, and Kyushu University, Japan; aims to first deploy a 2 km long tether in space and then maintain a formation by cooperatively controlling the main satellite and sub-satellite.⁵⁴ A similar mission for generating artificial gravity has been proposed in Ref. 107.

VI.E. Canadian Advanced Nanospace eXperiment-4&5 (CanX-4&5)

The CanX-4&5 mission, led by the University of Toronto and primarily supported by Canadian Space Agency, is a dual-nanosatellite mission that aims to demonstrate satellite formation flying with sub-meter tracking error accuracy and low change in velocity (ΔV) requirements. Each nanosatellite, weighing less than 7 kg as shown in Fig. 7(b), is capable of position control to within 1 m and attitude control to within 1°. The satellites autonomously achieve formation maneuvers using a thruster with maximum thrust of 5 mN and total ΔV of 14 m/s. The CanX-4&5 nanosatellites were successfully launched into sun-synchronous LEO (altitude of 660 km, inclination of 98.2°) as secondary payloads in June 30, 2014 onboard the Indian PSLV-C23 launch vehicle from Sriharikota, India.^{55,56}

VI.F. KickSat

The KickSat project, led by Cornell University, is a citizen space exploration project to dispense hundreds of small ChipSats into LEO, assess their in-orbit performance, and study their re-entry characteristics. This project was “crowd-funded” using Kickstarter.⁵⁷ After launch, the central 3U CubeSat, shown in Fig. 8(a), would launch 104 small Sprite ChipSats, each of size $32 \times 32 \times 4$ mm and weighing less than 7.5 gram. The mission was launched into LEO (altitude of 325 km, inclination of 51.6°) as secondary payloads on SpaceX’s Dragon launch vehicle from Cape Canaveral, FL in April 18, 2014. The ChipSats could not be deployed due to timer reset and the satellite reentered on May 15, 2014.⁵⁸

VI.G. CubeSat Proximity Operations Demonstration (CPOD)

The CPOD mission, led by Tyvak Nano-Satellite Systems and funded by NASA’s Space Technology Mission Directorate, aims to demonstrate rendezvous, proximity operations, formation flying, and docking in LEO using a pair of duplicate 3U CubeSats with deployable solar panels. The mission is scheduled for launch in Fall 2015 through NASA’s ELaNa program.^{59,60}

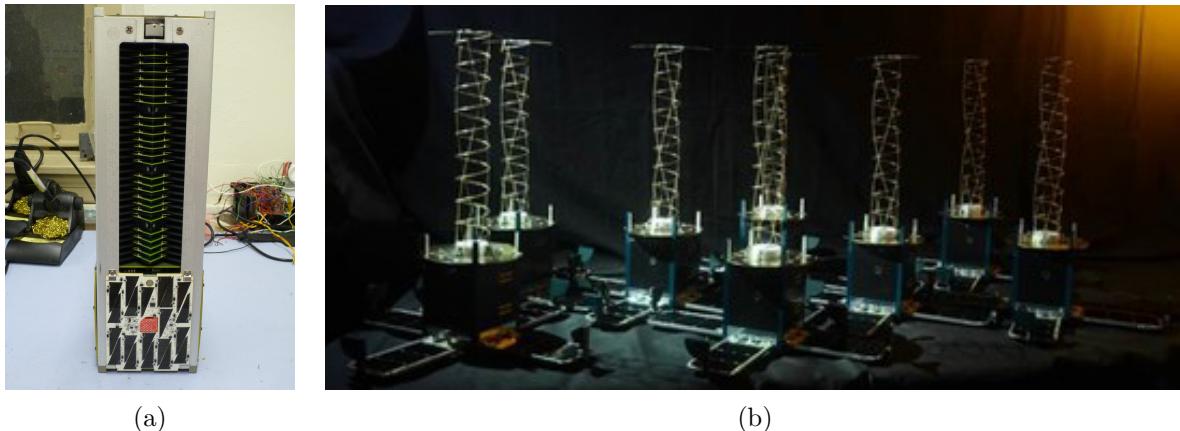


Figure 8: (a) KickSat with Sprite ChipSats (image credit: Cornell University¹⁰⁸). (b) Prometheus CubeSats (image credit: Los Alamos National Laboratory⁶⁴).

VI.H. TW-1

The TW-1 project, led by Chinese Academy of Science, aims to demonstrate autonomous formation flying with two CubeSats and inter-satellite communication using software-defined radio. The project consists of one 3U CubeSat and two 2U CubeSats and is scheduled for launch into LEO in May 2015.⁶¹

VI.I. Humanitarian Satellite Constellation (HumSat)

The HumSat mission concept, led by ESA, is an international educational initiative for building a constellation of nanosatellites for providing worldwide communication capabilities to areas without infrastructure. The aim is to deploy a worldwide constellation of CubeSats to support humanitarian and emergency applications, and to monitor parameters related to climate change. Nineteen universities worldwide have expressed their interest in developing the satellites of the global constellation.^{62,63}

VI.J. Prometheus

The Los Alamos National Laboratory launched eight Prometheus 1.5U CubeSats, where each satellite weighed 2 kg as shown in Fig. 8(b), in order to demonstrate the capability of transferring audio, video, and data files from man-portable, low-profile, remote field units to deployable ground stations terminals using over-the-horizon satellite communications. The eight satellites were launched into circular LEO (altitude of 500 km, inclination of 40.5°) as secondary payloads on a Minotaur-1 rocket for Wallops Island, VA, in November 19, 2013.^{64,65}

VI.K. UIUC-JPL Formation Flying Mission

This conceptual mission, led by the University of Illinois at Urbana-Champaign (UIUC) and funded by JPL, aims to launch four or six CubeSats into LEO to demonstrate formation flying capabilities in space as shown in Fig. 9(a). The four CubeSats will maintain a tetrahedron formation in space while the six CubeSats will demonstrate reconfiguration between multiple J_2 invariant relative orbits. Currently available thrusters (or position actuators) and relative position sensors are the major technological bottlenecks for formation flying CubeSat missions with mission life longer than a month.⁶⁶

VI.L. Swarms of Silicon Wafer Integrated Femtosatellites (SWIFT)

The SWIFT mission, led by JPL, UIUC, and Scientific Systems Company, Inc. and funded by the Defense Advanced Research Projects Agency (DARPA); aims to launch a swarm (100s to 1000s) of 100-gram-class femtosatellites into LEO for applications like sparse aperture arrays and distributed sensor networks. The swarm will be capable of forming three-dimensional shapes and maintaining them in a fuel-efficient manner. Each femtosatellite, weighing 100 grams as shown in Fig. 9(b), will house the communication system,

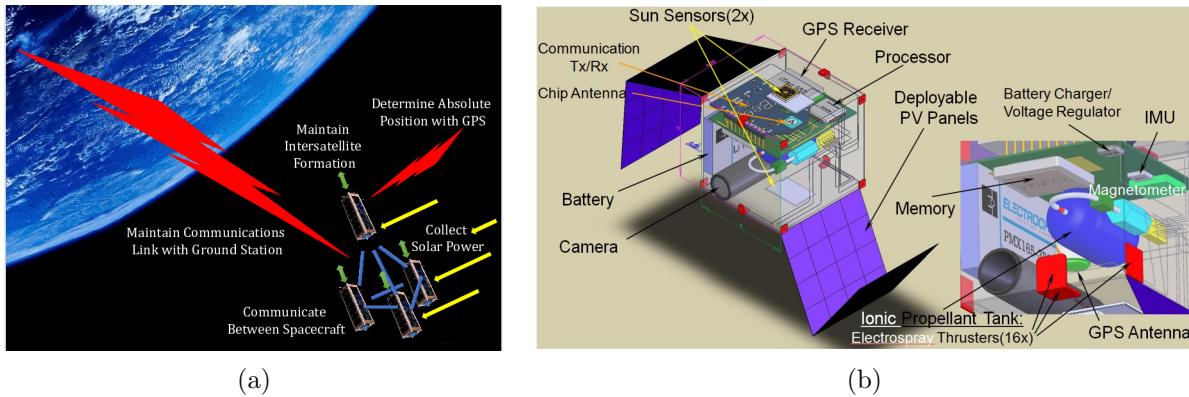


Figure 9: (a) Overview diagram of the UIUC-JPL FF mission, where 4 CubeSats maintain a tetrahedron formation in LEO (image credit: UIUC⁶⁶). (b) Notional design of femtosatellite with miniaturized warm gas hydrazine system (total power of 1.7 W, total mass of 104.7 grams, size of $4 \times 4 \times 4.25$ cm) (image credit: JPL³)

attitude and position sensors, power unit, command and data unit, and the propulsion unit. The successful implementation of the femtosatellite swarm hinges on successful miniaturization of the propulsion system, the multichip modules, and electronics for long-distance communication.³

VII. Conclusion

In this paper, we present a summary of thirty-nine multi-satellite missions in various stages of development. These small satellite missions are categorized based on their mission type, number of satellites, constellation or formation flying requirement (see Fig. 1), mission status, leading organization, and funding source (see Fig. 2). A large number of these multi-satellite missions are led by universities around the world (twenty one missions). Earth science missions are the most popular (twenty missions), followed by technology demonstration missions (twelve missions). For twenty four of these multi-satellite missions, a constellation is sufficient. Only twelve missions actually require formation flying capability, where the dynamic states of the satellites are coupled through a common control law. Among these twelve FF missions, ten missions use or aim to use only two to three small satellites. The three AeroCube-4 satellites have already successfully demonstrated formation flight and reconfiguration in space. The recently launched CanX-4&5 nanosatellites and the CPOD mission, if successful, will set the bar for state-of-the-art formation flying, rendezvous, and docking capabilities in space. Note that currently there are only two conceptual FF missions, namely the UIUC-JPL FF mission and SWIFT, which envision using four or more small satellites.

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