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CubeSat evolution: Analyzing CubeSat capabilities for conducting science missions

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A R T I C L E I N F O

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A B S T R A C T

Traditionally, the space industry produced large and sophisticated spacecraft handcrafted by large teams of engineers and budgets within the reach of only a few large government-backed institutions. However, over the last decade, the space industry experienced an increased interest towards smaller missions and recent advances in commercial-off-the-shelf (COTS) technology miniaturization spurred the development of small spacecraft missions based on the CubeSat standard. CubeSats were initially envisioned primarily as educational tools or low cost technology demonstration platforms that could be developed and launched within one or two years. Recently, however, more advanced CubeSat missions have been developed and proposed, indicating that CubeSats clearly started to transition from being solely educational and technology demonstration platforms to offer opportunities for low-cost real science missions with potential high value in terms of science return and commercial revenue. Despite the significant progress made in CubeSat research and development over the last decade, some fundamental questions still habitually arise about the CubeSat capabilities, limitations, and ultimately about their scientific and commercial value. The main objective of this review is to evaluate the state of the art CubeSat capabilities with a special focus on advanced scientific missions and a goal of assessing the potential of CubeSat platforms as capable spacecraft. A total of over 1200 launched and proposed missions have been analyzed from various sources including peer-reviewed journal publications, conference proceedings, mission webpages as well as other publicly available satellite databases and about 130 relatively high performance missions were downselected and categorized into six groups based on the primary mission objectives including "Earth Science and Spaceborne Applications", "Deep Space Exploration", "Heliophysics: Space Weather", "Astrophysics", "Spaceborne In Situ Laboratory", and "Technology Demonstration" for in-detail analysis. Additionally, the evolution of CubeSat enabling technologies are surveyed for evaluating the current technology state of the art as well as identifying potential areas that will benefit the most from further technology developments for enabling high performance science missions based on CubeSat platforms.

1. Introduction

The historic launch of Sputnik 1 in 1957 marked the beginning of the space age [1]. Subsequently, over the last 60 years hundreds of satellites were launched for a variety of purposes such as Earth Science [2,3], Astronomy and Astrophysics [4], Planetary Science [5], and Heliophysics [6,7]. Traditionally the space industry produced large and sophisticated spacecraft handcrafted by large teams of engineers. The development and launch of such spacecraft require significant resources within the reach of only a few large government-backed space agencies such as The National Aeronautics and Space Administration (NASA) and The European Space Agency (ESA) among others. The satellite launch mass gradually increased and reached peak values in the late 1990s and early 2000s as evidenced by a massive 8.2 tonne Envisat Earth Observation satellite built by ESA [8] and the 5.7 tonne Cassini planetary exploration mission built by NASA in a collaboration with ESA and the Italian Space Agency (ASI) [9]. These large spacecraft were envisioned to reduce the cost per kg of payload launched and to increase synergistic measurements by incorporating multiple instruments in a single satellite bus. However, in reality, micro-vibrations, electromagnetic compatibility issues as well as different maturity levels of instruments could create significant engineering problems during the development [10]. Thus, the attention on smaller spacecraft with smaller instrument suites (or single sensors) increased over the last decade from both operational and engineering perspectives.

Recent advances in technology miniaturization enabled the space industry to build small spacecraft from readily available, low cost, low power and compact commercial-off-the-shelf (COTS) components.

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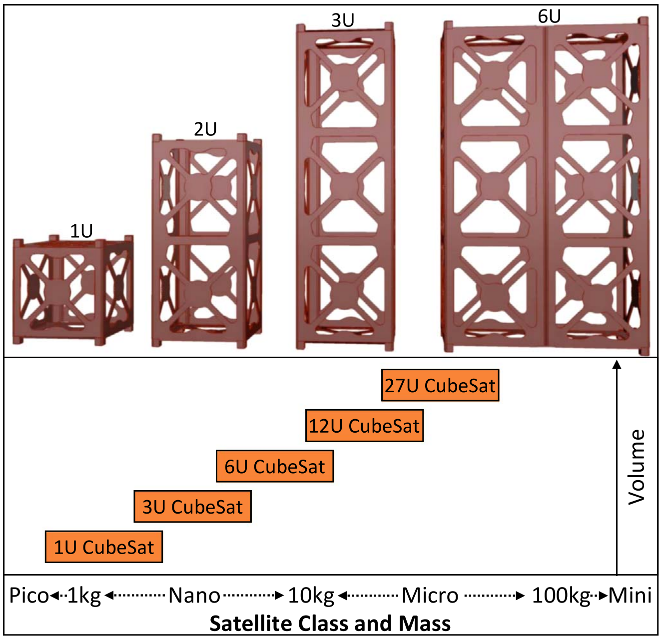

Fig. 1. CubeSat specifications in the framework of overall small satellite classifications (data modified from [12,16,22,267,268]). The volume of 1U unit equals to 10×10×10 cm^3.

Subsequently, this trend has inspired the development of a CubeSat concept [11]. The CubeSat standard was created by Stanford and California Polytechnic State Universities in 1999 [11,12], and it specifies that a standard 1U unit is a 10 cm cube (10×10×10 cm^3) with a mass of up to 1.33 kg (Fig. 1) [13]. A 1U CubeSat could either serve as a standalone satellite or could be combined together to build a larger spacecraft. For instance, a 3U CubeSat will have a form factor similar to three 1U CubeSats combined together. One of the main advantages of this standardization is to allow launch vehicle producers to adopt a common deployment system independent of the CubeSat manufacturer. Given the very successful nature of the smaller CubeSats such as 1U and 3U units, an advanced standard for larger (6U, 12U and 27U) CubeSats was brought forward for enabling much greater CubeSat capabilities [14]. Usually, small satellites are classified based only on their mass but in the case of CubeSat standard the volume is also considered. Fig. 1 gives a generally accepted classification for small satellites along with a comparison with the CubeSat standard.

CubeSats were initially envisioned primarily as educational or technology demonstration platforms that could be developed and launched within one or two years [11,12,15]. However, recently more advanced CubeSat missions have been developed and proposed indicating that CubeSats clearly started to transition from educational and technology demonstrating platforms to real low-cost missions with potential high value in terms of science return and commercial revenue [15]. CubeSats considerably decrease the cost and complexity of development and launch as compared to robust traditional satellites with redundant subsystems, as evidenced by observed dramatic increase in number of CubeSat launches over the last decade [16]. CubeSats could provide space exploration opportunities to small countries, educational institutions and commercial organizations around the world by allowing them to develop and launch their own spacecraft with relatively modest budgets of a few hundred thousand dollars [15,17]. Readily available inexpensive COTS components could also enable large constellations of small satellites with a potential to achieve comparable or even greater performance as compared to traditional spacecraft as well as to create a novel class of mission concepts [15,18]. Additionally, small satellites will have much lower impact from individual failures given their relatively low cost and short development times as compared to larger sophisticated satellites with budgets in excess of hundreds of millions of dollars [19] and on average five to ten years of development periods [20].

Originally, CubeSats were mainly developed by academic institutions and with only a small fraction of all launches being by a commercial sector, but this trend has been changing over the last few years and even though, academic institutions still account for a large fraction of all CubeSat development and launch, the contribution from the commercial sector is significantly increasing [16]. Recently, government agencies around the world also started to nurture CubeSat missions especially within academic institutions and non-profit organizations, for example, NASA's CubeSat Launch Initiative has already awarded launches to 125 CubeSat missions from 32 US states [21]. In addition of being excellent platforms for education and technology demonstrations CubeSats could potentially have much higher value in terms of scientific exploration [15] as well as in terms of commercial applications [16]. Despite the significant progress made in CubeSat research and development over the last decade some fundamental questions still habitually arise about the CubeSat capabilities, limitations and ultimately about their scientific and commercial value. The main objective of this paper is to evaluate the state of the art CubeSat capabilities with a special focus on advanced scientific missions and a goal of assessing the potential of CubeSat platforms as capable spacecraft for enabling low cost science quality missions. Some useful information could be found in previous CubeSat surveys [12,15,22,23] but neither of these surveys cover all scientific and commercial domains for all missions from around the world. Additionally, the dramatic increase in the number of CubeSat missions over the last few years combined with their short development times indicate that surveys older than 3–4 years [12,15] miss most of significant CubeSat developments. After the introduction section, Section 2 will provide a survey of the missions analyzed, then Section 3 will analyze CubeSat enabling technologies and limitations followed by comprehensive analyses of CubeSat payload capabilities in Section 4, and finally Section 5 will draw some conclusions.

2. State of the art survey of CubeSat missions

A total of over twelve hundred launched and proposed missions were analyzed from various sources including peer-reviewed journal publications, conference proceeding, mission webpages as well as other publicly available satellite databases (e.g. Gunter's Space Page [24]; FP7 NANOSAT database [25]; Saint Louis University CubeSat Database [26], eoPortal Directory [27]). The initial database was reduced to about 130 missions based on mission objectives and performance, all CubeSats carrying simple cameras or other simple sensors were excluded from the final database as much as possible. The list of all missions analyzed in this study is given in Table 1, while further details about the missions such as the spacecraft size, leading organization, primary objectives and launch status along with corresponding references are provided in Table A1 in Appendix A. Afterward the missions were roughly categorized into six groups based on the primary mission objectives including “Earth Science and Spaceborne Applications”, “Deep Space Exploration”, “Heliophysics: Space Weather”, “Astrophysics”, “Spaceborne In Situ Laboratory”, and “Technology Demonstration”. Although care was taken to categorize the missions as clearly as possible several missions could be listed under more than one category. For example, the BioSentinel mission could be identified both under “Spaceborne In Situ Laboratory” and “Deep Space Exploration” or similarly RainCube could be listed under both “Earth Science and Spaceborne Applications” and “Technology Demonstration” sections, but the missions were not duplicated in Table 1 as well as in Table A1 in Appendix A. All such missions appear only under one category, while in the discussions cross-references are provided as needed. This negligible ambiguity does not have any significant effect on the final conclusions of this study. The survey of the first five categories is exhaustive, while the “Technology

Table 1
Names and references of all missions analyzed.

Earth Science and Spaceborne Applications		**Earth Science and Spaceborne Applications (Continued)**		**Astrophysics (Continued)**	
QuakeSat	[227]	Hera Constellation	[140]	ASTERIA	[183]
ION	[228]	Lemur−2 Constellation	[138]	HaloSat	[185]
CanX−2	[45]	PlanetiQ Constellation	[141]	PicSat	[188]
CanX−6	[127]	**Deep Space Exploration**		**Spaceborne In Situ Laboratory**	
SwissCube	[229]				
PRISM	[230]	Lunar Flashlight	[147]	GeneSat−1	[190]
AISSat−1, −2, −3	[128,129]	Lunar IceCube	[148]	PharmaSat 1	[191]
		LunaH-Map	[149]	O/OREOS	[73]
SRMSAT	[117]	SkyFire	[150]	Lambdasat	[193]
AENEAS	[133]	NEAScout	[151]	SporeSat−1, −2	[92]
Hoʻoponopono 2 (H2)	[134]	OMOTENASHI	[153]	EcAMSat	[93]
Firefly	[125]	EQUULEUS	[153]	BioSentinel[a]	[94]
WNISAT 1	[231]	ArgoMoon	[153]	ChargerSat−2	[198]
MicroMAS−1, −2A, −2B	[112,113]	MarCO	[222]	Q-PACE	[195]
		INSPIRE	[161]	AOSAT	[196]
RACE	[232]	**Heliophysics: Space Weather**		**Technology Demonstration**	
Perseus-M1, -M2	[130]				
ExactView 9 (EV9)	[132]	RAX−1, −2	[165,166]	NanoSail-D2	[58]
AAUSAT4	[131]			STARE A, B, C	[256,257]
GHGSat-D (Claire)	[233]	DICE−1, −2	[71]		
Aoxiang-Sat	[234]	CSSWE	[167]	CANX−4, −5	[207]
SathyabamaSat	[118]	CINEMA, CINEMA 2, 3, 4	[164,169]	TechEdSat−3, −4	[223,224]
^{3}Cat−2	[109]				
RAVAN	[123]	SENSE SV1, SV2	[72]	GRIFEX	[202]
HARP	[122]	FIREBIRD−1, −2, −3, −4	[242,243]	LightSail-A, -B	[57]
IceCube (Earth−1)	[124]			OCSD-A, -B, -C	[203]
MiRaTA	[108]	ExoCube	[172]	Nodes-A, -B	[208]
EON-MW	[113]	PropCube 1, 3	[244]	VELOX-II	[209]
TROPICS Constellation	[114]	CADRE	[174]	ISARA	[76]
PolarCube	[115]	MinXSS, MinXSS−2	[41,68]	CPOD-A, -B	[210]
TBEx−1, −2	[235]			CANYVAL-X	[213]
PICASSO	[121]	Dellingr	[245]	DelFFi-Delta, -Phi	[211]
LAICE	[236]	ELFIN	[246]	QARMAN	[225]
PARIKSHIT	[237]	SEAM	[247]	InflateSail	[258]
Aalto−1	[238]	OSIRIS-3U	[248]	SAMSON-A, -B, -C	[214]
SeaHawk−1, −2	[239]	IGOSat	[249]	RANGE-A, -B	[212]
CIRiS	[119]	SORTIE	[250]	CanX−7	[226]
CIRAS	[120]	DIME	[251]	TEPCE-A, -B	[204]
RainCube	[102]	CeREs	[252]	CryoCube	[96]
TEMPEST-D	[116]	NEUTRON 1	[253]	FalconSAT−7	[259]
DUSTIE	[240]	ISX	[254]	AMODS	[215]
GOSTE−1	[106]	IT-SPINS	[255]	CubeRRT	[260]
CONASAT−1, −2	[136]	CuSP[a]	[152]	RECONSO	[261]
OPAL	[241]	**Astrophysics**		GLADOS	[262]
ARMADILLO	[107]			AeroCube−9 (LMPC)	[263]
Buccaneer	[135]	CXBN, CXBN−2	[176,177]	SurfSat	[264]
TRYAD−1, −2	[126]			AAReST	[216]
QB50 Constellation	[137]	BRITE-A, -U, -P1, -P2, -C1, -C2	[180]	MiTEE	[265]
Flock Constellation	[105]			iSat	[266]
Landmapper-BC, -HD	[130]	S-CUBE	[179]	^{3}Cat−1	[194]
Constellations	[139]				

[a] Deep-space CubeSat mission.

Demonstration” section only includes selected missions with significant developments, although the survey is as complete as possible, some missions particularly CubeSats currently in development might be missing from the analysis because of insufficient information available in the public domain at the time of writing of this paper.

Over the last fifteen years the small satellite industry experienced an explosive growth and most of this growth comes from the nanosatellite class, in particular CubeSats [28] as can be seen from the dashed line on Fig. 2. This study considers CubeSats ranging from 1U to 27U as well as several other nanosatellites not confined to the CubeSat form factor. Fig. 2 also shows the number of all publications (solid black line) and the publications specified as “articles” (double black line) found in the Web of Science search since the quantity and quality of publications can be a significant indicator of science return as well as can gauge the level of interest in CubeSat research [23]. The number of publications were retrieved by searching keywords such as "cubesat", "nanosat", "nanosatellite", "nano-sat", and "nano-satellite" both in singular and plural forms in titles, abstracts, keywords, and any control terms of all databases of Web of Science over the 2000–2015 period. NanoSat term could also include non-CubeSat missions, however the naming has been used in an interchangeable manner, particularly in the early years of the CubeSat era. As can be seen from Fig. 2 the number of total launches started to significantly increase around 2012 and this trend is predicted to continue over the next few years [28]. This movement in the small satellite industry is also reflected on the number of all publications as well as on the publications classified as articles indicating growing interest in CubeSat research as well as the onset of the high performance science missions based on CubeSat platforms.

Total of 471 CubeSats with a size of 1U and larger have been launched as of August 2016 for a variety of purposes and about 99% of all launches are within 1U to 3U range. The 3U platforms represent the largest fraction of all launches with about 57% share, while the 1U platforms represent about 29% of all launches (Fig. 3). To date, the 12U

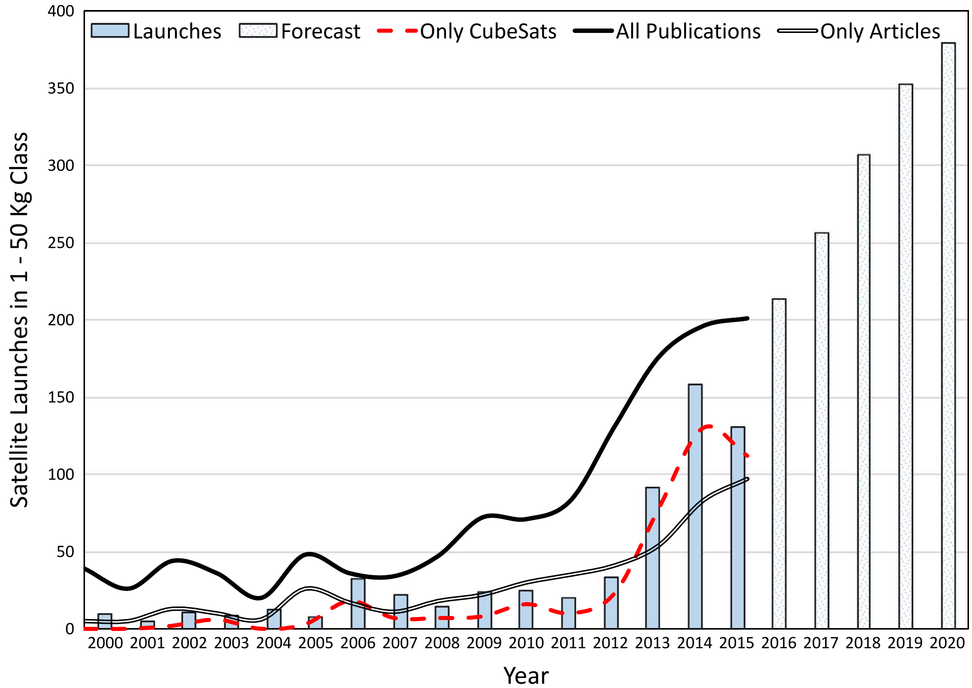

Fig. 2. Columns are historic and predicted satellite launches in 1–50 kg class (data from [16,28]). Solid black line shows all publications, double black line shows publications classified as "articles" in the Web of Science search, while the red dashed line shows total number of launches confined to the CubeSat form factor.

Aoxiang Zhixing (Aoxiang-Sat) satellite developed at Northwestern Polytechnical University (NPU) in China and launched in June 2016 is the largest CubeSat size launched [29]. Even though, large number of 1U CubeSats have been launched, the number of missions using larger platforms such as 3U and 6U are gaining significantly more traction over the last several years (Fig. 3), in fact, only a few science missions with relatively high performance were identified to have a size smaller than the 2U (Table A1), which seems obvious given the fundamental constraints of CubeSat platforms. Larger CubeSats such as 3U, 6U or 12U will become more common in the near future due to significantly increased capabilities, while smaller platforms will most likely continue to be utilized particularly for technology demonstrations as well as part of large satellite swarms in the future.

3. Enabling technologies

3.1. Structures

Structure is the primary chassis of spacecraft, which mechanically supports all spacecraft subsystems as well as it might serve as thermal and radiation shielding for sensitive components. Custom built and off-the-shelf structures are the two main options for a CubeSat chassis. The main advantage of off-the-shelf structures is their simplicity and flight heritage, whereas custom built structures could be adopted to a specific

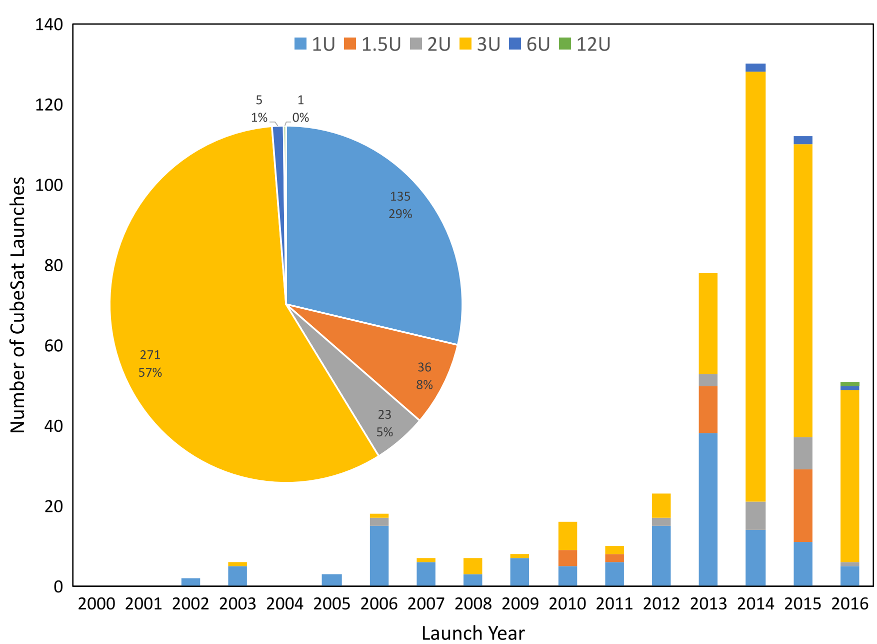

Fig. 3. Diagram showing all CubeSat launches as of August 2016 distributed among different CubeSat sizes for each year (columns). Whereas, the inset pie chart represents the fractions of all launches that belong to each CubeSat size.

mission complexity, payload and subsystem requirements although at the cost of extensive testing. Typically, CubeSat structures are made from aluminum [22] but recently 3D printed CubeSat structures are also garnering some interest among developers, and already several missions including 3U Tomsk-TPU-120 [30], 1U PrintSat [31], 2U QB50 UNSW EC0 [32] CubeSats started to utilize 3D printed structures.

There are multiple companies, such as Pumpkin [33], ISIS [34], Radius Space [35] and Clyde Space [36] among others [22], providing off-the-shelf structures ranging from 1U to 16U class CubeSats. Although a large proportion of all CubeSats launched to date have been in the 1U to 3U range [12,25,26], larger units such as 6U, 12U and even 27U are being explored for increased capabilities in a standardized manner similar to highly popular and successful 3U class CubeSats. However, deployers for larger CubeSats such as 12U and 27U are still in development, and currently there is no deployer with flight heritage for 27U spacecraft. Moreover, a recent trend in the nanosatellite market is the rise of integrated CubeSat platforms offered by several companies such as Tyvak [37] and Blue Canyon Technologies [38]. Tyvak [37] offers high performance integrated CubeSat Endeavor Platform ranging from 3U to 12U size whereas, Blue Canyon Technologies [38] offers high performance integrated XB line of CubeSat buses ranging from 3U to 27U size. NASA [22] report on small spacecraft technologies provides a detailed list of companies and offered platforms.

3.2. Power

Electrical power subsystem consists of a power source, energy storage, power distribution, regulation and control units [39]. Photovoltaic solar cells are the primary power source for CubeSats with the state of the art triple-junction solar cells achieving efficiencies between 27–33% [22]. Given the CubeSat surface area constraints solar cells can be either body-mounted or deployable depending on specific mission power requirements. Currently, power generation on 3U CubeSats can easily reach up to 20–30 W by using deployable solar panels [40–42]. Additionally, spacecraft usually need on-board energy storage capability to provide power during orbit eclipses as well as to satisfy peak power requirements of instruments. There is a wide range of battery types available in the market, such as high energy density lithium ion and lithium polymer batteries that can be utilized as primary or secondary power source for CubeSat missions [22]. Power distribution, regulation and control systems are often custom built by spacecraft designers based on their system requirements. Furthermore, there are several options of ready-made power management systems in the CubeSat market provided by companies such as Blue Canyon Technologies [43], Clyde Space [36], and GomSpace [44]. Overall, current CubeSat power subsystems offer adequate capabilities based on photovoltaic and battery technologies. However, development of more advanced and capable power subsystem might be required for interplanetary CubeSat missions that will go beyond Mars or the missions that will use high energy active instrument such as radars.

3.3. Propulsion

Very few of the early nanosatellite missions had propulsion systems [12] and in fact, the only propulsion system successfully used on a CubeSat as of 2011 was a cold gas thruster carried by 3U CanX-2 CubeSat launched in 2008 [15,45]. The need to have CubeSat compatible propulsion systems promoted strong research and development activities over the last several years [22]. Propulsion systems are vital in expanding CubeSat capabilities by enabling orbit change and raising, precise attitude control, formation flying as well as deorbiting capabilities at the end of the mission life in order to comply with orbital debris mitigation requirements [46]. In-space spacecraft propulsion systems can be generally divided into three categories including chemical, electric, and propellantless propulsion systems [47]. Generally, chemical propulsion systems can achieve higher thrust levels although with limited specific impulse compared to electric propulsion systems [39]. Whereas, propellantless systems such as solar sails do not utilize any propellant to produce thrust thus reducing the system complexity and mass, and potentially even enabling long term interplanetary missions [22].

Over the last 5 years several CubeSat missions were launched carrying propulsion systems such as cold gas thruster, pulsed plasma thruster, vacuum arc thruster, electrospray, resistojet as well as solar sail. Examples include AeroCube-8 two 1.5U CubeSats launched in 2016 featuring Scalable ion Electrospray Propulsion (SiEPro) system [48,49], BRICSat-P 1.5U CubeSat launched in 2015 featuring Micro-Cathode Arc Thruster (μCAT) propulsion system [50], TW-1A 3U CubeSat launched in 2015 [51], POPSAT-HIP 1 3U CubeSat launched in 2014 [52] and Delfi-n3Xt 3U CubeSat launched in 2013 [53] all carrying some type of cold-gas micropropulsion systems, STRaND-1 3U CubeSat launched in 2013 carrying pulsed plasma thrusters and water-alcohol resistojet propulsion system [54,55], SERPENS 3U CubeSat launched in 2015 carrying a pulsed plasma thruster [56] as well as some propellantless propulsion systems were launched such as solar sails on LightSail-A 3U CubeSat launched in 2015 [57] and solar sail on NanoSail-D2 3U CubeSat launched in 2010 [58].

Small spacecraft compatible electrical and chemical propulsion systems have advanced significantly over the last several years through intensive research and development activities enabling miniaturized propulsion systems for CubeSat class missions. Companies such as Busek Co. Inc. [59], VACCO [60], Aerojet Rocketdyne [61], Accion Systems [62] and Tethers Unlimited Inc. [63] offer different types of propulsion systems for CubeSats with specific impulses ranging from about 40 s to 4000 s and the total impulse available for CubeSat class missions can reach over 3700 Ns, whereas, the thrust ranges from μN to N levels [22,62]. In summary, as the maturity of in-space propulsion technologies continues to increase CubeSat developers will have multiple sophisticated propulsion systems available to utilize depending on specific mission requirements thus enabling more cutting-edge missions based on CubeSat platforms.

3.4. Guidance, Navigation and Control

A Guidance, Navigation and Control (GNC) system can be generally considered as a combination of the Orbit Determination and Control Subsystem (ODCS), which measures and maintains the position of the satellite's center of mass as a function of time, and the Attitude Determination and Control Subsystem (ADCS), which measures and maintains the satellite's orientation about its center of mass [39,64]. In Earth orbit, a Global Navigation Satellite System (GNSS) such as GPS or Galileo is the primary technique for spacecraft position determination. Whereas, deep space navigation is performed by using radio transponders, such as the Iris CubeSat compatible deep space radio built by the Jet Propulsion Laboratory, in combination with the Deep Space Network (DSN). Iris weighs less than 300 g and is scheduled to fly on the INSPIRE 3U CubeSat [65].

ADCS uses sensors such as star trackers, Sun sensors, Earth sensors, and magnetometers to determine spacecraft attitude and uses actuators such as reaction wheels, magnetorquers, and thrusters to stabilize and orient spacecraft in a desired direction [22,64]. CubeSat ADCS has dramatically improved over the last decade facilitated by the development of state of the art miniaturized star trackers capable of achieving precise 3-axis attitude determination with an arcsecond accuracy [22]. Additionally, several companies are offering integrated units for precise 3-axis control, which combine different GNC components into a single package to provide cutting-edge solutions. For instance, Blue Canyon Technologies offers integrated CubeSat XACT attitude control system with a stated spacecraft pointing accuracy of better than 0.007° (1-sigma) for 3 axes, which occupies only 0.5U volume [66], the first XACT system flown on the MinXSS CubeSat was able to achieve control system errors of less than 16 arcseconds RMS on all three axes based on preliminary on-orbit data [67,68]. Another example of highly integrated 0.5U system, which can achieve pointing accuracy of 0.057° (1-sigma), is offered by Tyvak International [69]. Overall, CubeSat GNC field is a relatively mature area with numerous flight proven components available in the market [22] as well as available highly integrated CubeSat systems already flown as of 2016 [41], although some future improvements in GNC especially for interplanetary missions will be necessary given the increasing number of deep space CubeSat mission proposals over the last few years.

3.5. Communications

The communication subsystem is the interface between the satellite and the ground station, which allows spacecraft to downlink its payload and housekeeping data to the operation center, to transmit operator commands to spacecraft as well as to establish intersatellite communications. Most of the early CubeSat missions used VHF and UHF radio frequency (RF) communications with typical data rates of 1.2 and 9.6 Kbps [12,70]. However, the DICE 1.5U CubeSat mission launched in 2011 was able to achieve higher data rate of 3 Mbps on UHF band [71]. Additionally, several CubeSat missions achieved higher data rates of up to a few Mbps through S-band communication systems [12,70,72,73]. These low rates are a major limiting factor for making cutting-edge miniaturized science instruments compatible with the CubeSat standard since the payload will generate significantly more data than could possibly be downlinked at these rates [15,74]. However, state of the art communication systems using higher bands such as X-band started to become compatible with CubeSat standard enabling much greater downlink capabilities for CubeSats [22,75]. Additionally, CubeSat compatible high-speed Ka-band communication systems are also gradually becoming available, which will improve CubeSat data rates by orders of magnitude in the near future [76,77]. An example of an emerging Ka-band communication system includes the ISARA 3U CubeSat, which will demonstrate downlink rates of about 100 Mbps by using a high-gain reflectarray antenna (~35 dB of gain) integrated into a commercially available deployable solar array combined with a low power transmitter, a high accuracy ADCS achieving 0.2° pointing accuracy, and a Ka-band ground station [76,78], another example is 6U CubeSat compatible Ka-band transmitter (0.63W RF output power) developed by Aquila Space, which is estimated to achieve downlink data rates of up to 40 Mbps with a volume of 1U and mass of 1 kg [77].

The next breakthrough in CubeSat communications will be the adoption of free-space optical communications technology to CubeSat class missions. Laser communication has the potential to dramatically increase the data rates of up to several Gbps [79] thus potentially eliminating the downlink constraints of CubeSat platforms. CubeSat laser communication is steadily progressing and is expected to be space demonstrated in 2016 by the NASA Optical Communication and Sensors Demonstration (OCSD) program, which consists of one 1.5U CubeSat pathfinder mission launched in October 2015 [80] and two more 1.5U CubeSats scheduled to be launched in 2016 to demonstrate data rates of about 500 Mbps and even possibly approaching Gbps rates [79,81].

3.6. Command and data handling

The command and data handling subsystem of spacecraft is responsible for receiving, validating, decoding, and distributing commands to other subsystems as well as gathering, preparing, and storing housekeeping and mission data for downlink or onboard utilization. In general, the command and data handling subsystem also integrates additional functions such as computer health monitoring, security interfaces, and spacecraft timekeeping [39]. Recent advances in commercial-off-the-shelf microcontroller technologies enable high performance capabilities although with higher vulnerability to space radiation. Common on-board data handling systems for CubeSat include FPGAs [82], MSP and PIC microcontrollers, as well as microcontrollers based on high performance and power efficient ARM architecture [12,22]. Furthermore, several promising open source hardware and software development platforms such as Arduino, BeagleBone, and Raspberry Pi are gaining increasing interest among CubeSat developers, these platforms could hold high value by providing simplified and cost effective tools to small satellite developers [22].

CubeSat onboard data storage can be as low as several KBs or MBs and depending on the mission requirements the total storage capability could be increased up to hundreds of GBs by taking advantage of commercial flash memory technologies [15,83,84]. The fundamental limiting factor for CubeSat is the bottleneck in the data downlink and not the onboard data storage, and any further increase in storage capabilities without corresponding improvements in the downlink rates will not be useful [15]. Overall, the CubeSat command and data handling subsystems are relatively mature field with wide range of available options, although as CubeSat designs and applications evolve radiation hardened components will be required to extend the mission lifetime in LEO and to enable deep space missions.

3.7. Thermal control

On orbit, spacecraft experience extreme temperature fluctuations over short time periods (e.g. minutes to hours), when in the Sun the temperature can reach over +100 °C whereas in eclipse the temperature can get well below −100 °C [39]. Thus thermal control is critical for successful operation and survival of satellite and its payload. Passive and active thermal control techniques are used for regulating spacecraft thermal budget based on mission requirements [85]. The thermal budget of spacecraft is influenced by external heat inputs from direct sunlight, which is the most important external heat source, sunlight reflected off the Earth or other planets and moons (albedo), and infrared (IR) energy emitted from a surface or atmosphere of the central body in addition to heat generated by internal components of the satellite. The thermal control of spacecraft is attained by balancing the heat inputs against the energy emitted by the satellite [39,85]. To date, all CubeSat missions were deployed in Low Earth Orbit (LEO) but it is envisioned that in the near future CubeSat missions will go far beyond LEO (e.g. MarCO [86], Lunar Flashlight [87], INSPIRE [88], NEAScout [89]) thus exposing interplanetary CubeSat missions to wide range of thermal environments usually determined by the distance between the sun and spacecraft as well as IR and albedo loads of the central body [85].

Passive thermal control utilizes no power input and can be accomplished by variety of techniques such as Multi-Layer Insulation (MLI), thermal coating, Sun shields, thermal straps, louvers, radiators and heat pipes. The passive approach has significant advantages such as reliability, low mass, volume and cost, which makes it particularly appealing choice for CubeSats given their power, mass and volume constraints [22]. However, active thermal control systems, that rely on power input for operation, may be needed for more efficient thermal control of missions requiring precise temperature ranges such as cryogenic cooling for optimal performance (e.g. high precision IR sensors) [15] or biological payloads [22,85]. Biological payloads with challenging thermal control requirements are drawing significant interest over recent years as evidenced by increasing number of CubeSat missions such as PharmaSat [90], O/OREOS [91], SporeSat [92], EcAMSat [93], and Biosentinel [94]. Examples of active control systems include thermal straps, heaters and cryocoolers [22,39].

Traditionally thermal insulation such as MLI blankets and surface coatings are used for regulating incoming heat and avoiding excessive heat dissipation in order to maintain the operational temperature limits of spacecraft subsystems and some temperature sensitive payloads such as bioactive payloads. Traditional thermal insulation could be combined with active control systems for more effective and precise thermal regulation. Examples of this hybrid approach include Pharmasat [90], and BioSentinel [94] CubeSats. PharmaSat is a 3U mission conducting biological experiment in LEO. The bioactive payload was insulated by MLI, gold plated interior payload enclosure surfaces, low thermal conductivity materials. This design approach allows the spacecraft to endure cold temperatures and an active thermal control system consisting of 2 W Minco heaters was used to increase the temperature of the biological payload up to 27 °C [90]. The BioSentinel 6U mission scheduled to be launched in 2018 is another example utilizing hybrid active-passive thermal control for conducting biological experiments in deep space. It uses passive thermal insulation and coatings to cold bias the payload and then to utilize kapton strip heaters and sensors to control the payload temperature at 23 °C ± 1 °C over the 12–18-month planned mission lifetime [94].

Deployable sunshield is another state of the art passive thermal control system being developed in CryoCube-1 by Sierra Lobo, Inc. in collaboration with the NASA Kennedy Space Center, the 3U CubeSat is planned to be launched in 2016 [95,96]. The sunshield is estimated to achieve temperatures below 100 K and with an addition of an active cooling system the temperature can get below 30 K [95] and it can maintain these temperatures over a several month long mission lifetime. The CryoCube-1 spacecraft design allocates 1.5U volume for a payload [97] thus enabling potential high value payloads with cryogenic cooling requirements for CubeSat form factor. Additionally, several active cryocoolers potentially compatible with CubeSat platforms are under development by several companies although none of them have flown on CubeSats to date. Examples of compact cryocoolers include the CryoTel DS1.5 Stirling Cryocooler developed by Sunpower, Inc. which has a nominal heat lift of 1.4 W at 77 K consuming 30 W input power with a 1200 g mass [98]; 900 g micro pulse tube cooler developed by the Northrop Grumman, which is capable of cooling to temperatures less than 45 K [99]; micro pulse tube cryocooler developed by Lockheed Martin Space Technology and Research Lab, the compact system can be accommodated in 0.5U volume of a CubeSat with a mass of 328 g and can provide cooling loads of 0.85 W at 150 K with 10 W of input power [100,101].

4. Payload capabilities

4.1. Earth science and spaceborne applications

Earth is a dynamically evolving complex system encompassing several subsystems such as atmosphere, lithosphere, hydrosphere, cryosphere, and biosphere [2]. Spaceborne Earth Observation (EO) helps to expand our knowledge of the Earth as an integrated system as well as to better understand its natural evolution and human induced environmental changes on a wide range of temporal and spatial scales (Fig. 4). In addition of having a tremendous scientific value, Earth Observation also has significant economic incentives such as improved exploitation of natural resources, better prediction of climate change, weather, natural hazards, and emergency management and security, which could potentially worth billions of dollars to economies around the world [2].

Active and passive sensors are two main types of remote sensing instruments utilized in spaceborne Earth Observation (Fig. 4). Active instruments such as radars, lidars, laser and radar altimeters, and scatterometers generate their own electromagnetic radiation to illuminate the target object then to observe the reflected or backscattered portion of the transmitted radiation, thus enabling day and night capabilities independent of solar illumination. The major limiting factor for implementing active instruments on CubeSat platforms is usually high power requirements of these type of sensors [15]. To the date of writing this manuscript no active sensor has flown on a CubeSat platform and the preliminary feasibility assessment of remote sensing instruments conducted by Selva and Krejci [15] in 2011 determined that radars, lidars and virtually any active instrument is not compatible with CubeSat platforms because of the stringent power and size constraints. However, recent technological advances are envisioned to change this assessment and enable novel mission architectures carrying active instruments in the near future. RainCube is the first CubeSat mission with an active radar payload being developed at NASA Jet Propulsion Laboratory and is expected to be launched in 2017 [102]. RainCube is a 6U spacecraft to enable Ka-band (35.75 GHz) precipitation radar technology as well as a compact deployable Ka-band antenna on a low-cost CubeSat platform (Table 1) [103]. Additionally, miniaturized imaging radars are also garnering significant interest and SRI International already started to develop a CubeSat compatible S-band radar system capable of performing interferometric synthetic aperture radar (InSAR) operations [104]. The successful demonstration of the feasibility of radar payloads on a CubeSat platform will open multiple high value missions to CubeSats as well as will enable low-cost LEO radar constellations, prohibitively expensive in the case of traditional large space platforms, for achieving unprecedented temporal resolutions essential for studying processes occurring on a short timescale.

Whereas, the passive sensors such as radiometers, spectrometers, GNSS radio-occultation sounders and optical imagers do not have their own radiation source and detect reflected or emitted energy for observing the target of interest with the sun being the most common source of the secondary radiation. Only recently Earth observation community started to fully utilize CubeSat capabilities for addressing challenging questions and to date, most of the launched EO CubeSat missions carried low to moderate resolution optical sensors for imaging the Earth with as high as 3–5 m resolutions achieved by 3U CubeSats developed and launched by a commercial EO company Planet Labs Inc. [105]. Furthermore, several launched and proposed missions such as 3U CanX-2 [45], 3U GOSTE-1 [106], and 3U ARMADILLO [107], 3U MiRaTA [108] use GNSS radio occultation technique, which detects radio signals transmitted by Global Navigation Satellite System (GNSS) for observing various atmospheric parameters such as temperature, pressure, density, humidity as well as ionospheric total electron content (TEC) and electron density profiles on a global scale and with all-weather high resolution for improving weather prediction, climate change monitoring, and space weather forecasting. Additionally, GNSS reflectometry such as the technique used by 6U ^{3}Cat-2 mission [109] developed at Universitat Politécnica de Catalunya could be used to conduct ocean and ice altimetry and scatterometry, to monitor soil moisture, biomass, wind speed, and wind direction [110,111].

Miniaturized radiometers and spectrometers are another set of passive sensors garnering significant interest promoted by their evident compatibility with the CubeSat platforms in terms of power, pointing, and aperture size. Significant research efforts have been focused on developing CubeSat compatible high performance microwave radiometers in Massachusetts Institute of Technology (MIT) with already several missions launched or currently in development including 3U MicroMAS-1, MicroMAS-2, MiRaTA, 12U EON-MW missions and TROPICS Constellation. MicroMAS-1 mission launched in 2014 was intended to demonstrate and operate a 9-channel passive microwave spectrometer observing near the 118.75 GHz oxygen absorption line, however, no payload data was downlinked due to a transmitter failure [112,113]. The MicroMAS-2 mission consists of two 3U CubeSats equipped with a 12-channel passive microwave spectrometer providing imagery near 90 and 206 GHz, temperature sounding near 118 GHz, and moisture sounding near 183 GHz [113]. MiRaTA is a 3U mission combining advanced atmospheric remote sensing V- and G-band radiometers (52–58 GHz, 175–191 GHz, and 203.8–206.8 GHz) with a compact GNSS radio occultation sensor [108]. Whereas, EON-MW is a 12U high-performance, high-resolution mission combining all advances of MicroMAS and MiRaTA missions for observing 22 channels from 23 to 183 GHz in order to provide data continuity with the

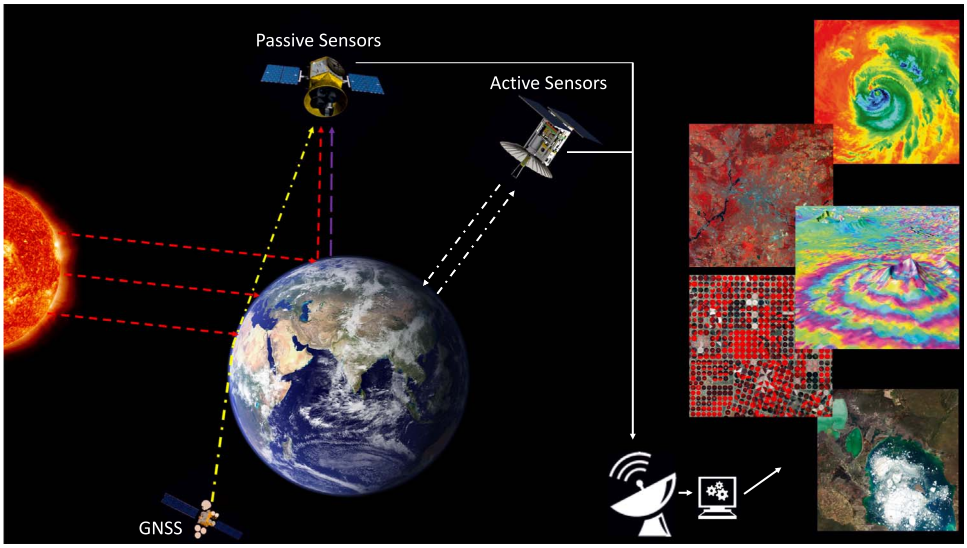

Fig. 4. Overview of Earth Observation from space (individual images modified from: NASA/JPL-Caltech/ESA/Copernicus).

existing AMSU and ATMS microwave sounders [113]. TROPICS (Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats) constellation consists of 12 identical 3U CubeSats for performing microwave observations with a median refresh rate of about 30 min at all longitudes and ±40° latitudes by using a 12-channel passive microwave spectrometer to provide imagery near 90 and 206 GHz, temperature sounding near 118 GHz, and moisture sounding near 183 GHz from three low Earth orbital planes. The TROPICS constellation will enable observation of the thermodynamics of the troposphere and precipitation structure for storm systems at exceptional spatial and temporal resolutions [114]. Other passive microwave radiometer missions include 3U PolarCube performing tropospheric temperature sounding by using 8 channels centered around the 118.75 GHz oxygen emission line [115], and 6U TEMPEST-D mission using a 5-frequency radiometer at 89, 165, 176, 180 and 182 GHz for global observation of time evolution of precipitation [116].

The infrared region of the electromagnetic spectrum also spurred significant interests among developers, which resulted in several missions already launched or currently being developed for answering various Earth science questions, moreover some CubeSat missions also explore other regions of the electromagnetic spectrum such as submillimeter wave (IceCube) and gamma ray (Firefly) regions (Table 1). For instance, 3U CanX-2 [45], 10.9 kg SRMSAT [117], and 2U SathyabamaSat [118] missions use atmospheric infrared spectrometers to monitor several greenhouse gases in the atmosphere. Other notable examples include 6U CIRiS, developing an uncooled imaging infrared (7.5–13 μm) radiometer designed for high radiometric performance for land and water resource management [119]; 6U CIRAS, measuring hyperspectral infrared atmospheric radiances to acquire temperature and water vapor in the lower troposphere with a performance similar to traditional spacecraft [120]; 3U PICASSO, investigating ozone distribution in the stratosphere, the air temperature profile up to the mesosphere, and the electron density and temperature in the ionosphere by using a sweeping Langmuir probe and a visible and near-infrared hyper-spectral imager [121]; 3U HARP, studying microphysical properties of aerosols and clouds to narrow uncertainties in climate change by using a hyperangular imaging polarimeter [122]; 3U RAVAN, observing top-of-the-atmosphere Earth-leaving fluxes of total and solar-reflected radiation by using a compact and accurate radiometer [123]; 3U IceCube (Earth-1), observing global cloud ice from space with 883 GHz submillimeter-wave receiver [124]; and finally 3U Firefly [125] and TRYAD-1 and 2, [126] exploring Terrestrial Gamma-ray Flashes (TGFs) in order to advance our understanding of this atmospheric phenomenon. The complete list of the missions is provided in Table 1, while a more detailed information such as the current status and primary objectives are provided in Table A1 in Appendix A.

Earth applications from space are also attracting increasing interest given the fast development cycle and relatively low cost of CubeSat and nanosat class missions. Although to date only few spaceborne applications were proposed such as ship tracking through detection of Automatic Identification System (AIS) signals transmitted by vessels, the AIS technology is already being utilized by the following missions: 6.5 kg Generic Nanosatellite Bus (GNB) CanX-6 [127]; 7 kg GNB AISSat-1, 2, 3 [128,129]; 6U Perseus-M1, M2 [130]; 1U AAUSAT4 [131]; and 5.5 kg GNB ExactView 9 (EV9) [132] as well as cargo container tracking over the open ocean with a WiFi-like transceiver employed by 3U AENEAS mission [133]. CubeSats could also be used for performance monitoring and calibration of radar tracking stations around the world such as the 3U Ho'oponopono 2 (H2) [134] and Buccaneer [135] missions. Another interesting spaceborne application includes the utilization of CubeSat platforms for relaying environmental data collected by in situ remote ground sensors to the mission center. For example, two 8U CONASAT spacecraft constellation will gather environmental data such as rain volume, temperature, humidity, air pollution, ocean stream from remote Data Collecting Platforms (PCD) distributed throughout Brazil including very hard to reach areas such as the Amazon rainforest and unpopulated regions in the central Brazil and then to retransmit the data to the mission center [136].

Multipoint sensing and enhanced coverage is one of the main strength of CubeSat platforms and more and more mission architectures based on tens or even hundreds of small satellites will most likely emerge both in science community as well as in the commercial sphere enabled by low-cost CubeSat platforms for achieving unprecedented spatial and temporal resolutions impractical with traditional large spacecraft. In fact, over the last few years several scientific and commercial missions started to exploit CubeSat capabilities to perform multipoint sensing or developing large EO constellations. Notable examples of proposed or currently under development multi-spacecraft constellations include QB50 [137], TROPICS [114], Flock [105], Lemur-2 [138], Landmapper-BC, HD [130,139], Hera [140], and PlanetiQ [141]. The QB50 mission consists of a network of 50 2U or 3U CubeSats built by international university groups to conduct science quality research in a mostly unexplored lower thermosphere between 200 and 380 km altitude. Most of the QB50 spacecraft will carry one of the three science instruments including Ion-Neutral Mass Spectrometer (INMS), Flux-Φ-Probe Experiment (FIPEX) and multi-

Needle Langmuir Probe (m-NLP) to conduct in-situ atmospheric measurements during a few month of operations [137]. Planet's Flock is the largest constellation of commercial Earth imaging spacecraft, which already launched 133 Dove spacecraft as of May 2016 [142]. The primary goal of Planet's CubeSat constellation is to image all landmasses of Earth at a resolution of 3–5 m with a daily revisit [105]. The low cost and short development time of CubeSat missions enable rapid iterations allowing to upgrade the system by integrating lessons learned and new technological advances for example, Planet launched its first spacecraft in April 2013 and as of mid 2016 the Dove CubeSats have seen 14 spacecraft hardware revisions [142]. Other proposed commercial Earth imaging missions include initially nine 12U spacecraft constellation from Hera Systems Inc. to produce daily imagery and video of Earth at 1 m resolution [140] as well as Landmapper-BC constellation consisting of ten 6U CubeSats being developed by Aquila Space/Astro Digital to collect multispectral Earth imagery of arable and coastal regions with a resolution of 22 m in Green, Red, and NIR spectral bands, while the Aquila Space/Astro Digital's Landmapper-HD constellation will consist of twenty 16U spacecraft for collecting multispectral Earth imagery of arable and urban areas with a resolution of 2.5 m in Blue, Green, Red, Red Edge, NIR spectral bands [130,139].

Another area that is attracting increasing interest from commercial sector is the utilization of CubeSat platforms as commercial weather satellites by employing GNSS radio occultation technique. Spire Global, Inc and PlanetiQ, LLC are two notable examples that are developing CubeSat based GNSS radio occultation satellites. Spire Global has already launched 14 3U CubeSats as part of Lemur constellation to provide atmospheric measurements by GNSS radio occultation sensor as well as AIS data for global ship tracking [143]. Spire's commercial constellation is still in development and could evolve into a large constellation reaching a size of even hundreds of CubeSats for achieving unprecedented temporal and spatial coverage in the near future [144]. Whereas, PlanetiQ is intending to launch an initial constellation consisting of 12 6U spacecraft by 2017 and with a possibility of expanding the constellation to 18 spacecraft by 2020 to provide high quality atmospheric sounding by GNSS radio occultation sensor [141,145]. These commercial weather CubeSat constellations will dramatically improve weather prediction by providing tens of thousands of near real-time GNSS radio occultation measurements of atmosphere every day [138,141].

In summary, even though CubeSats are now gradually being utilized for Earth observation, the initial missions demonstrated that CubeSat platforms could potentially be used to conduct high quality Earth science and enable new missions in addition to being utilized for spaceborne applications. CubeSats could excel at targeted missions and multipoint observations as well as could augment the capabilities of traditional large Earth science missions by combining several low-cost CubeSat platforms. Additionally, their low cost and fast development cycle could potentially enable exceptional scientific missions based on distributed space system architectures such as swarms and constellations for detecting unprecedented temporal and spatial details, thus combining a high spatial resolution intrinsic to LEO spacecraft with a high temporal resolution similar to geostationary spacecraft. Furthermore, CubeSat platforms could possibly be utilized as gap fillers between traditional missions to insure long-term observational continuity of critical data sets.

4.2. Deep space exploration

To date, all CubeSat missions were launched into Low Earth Orbit (LEO) but this trend is about to change when several CubeSat missions will be propelled beyond LEO starting as soon as in 2017. Total of at least 15 CubeSat missions are scheduled to go beyond LEO during 2017–2018 period including 14 6U and one 3U CubeSat missions. The 13 of these 6U CubeSats will be launched together as a secondary payload onboard the first flight of NASA's Space Launch System (SLS) named Exploration Mission-1 (EM-1) in 2018, thus offering an unique opportunity for CubeSats to conduct science and technology missions in deep space [146]. The 10 confirmed 6U CubeSats on EM-1 include Lunar Flashlight [147], Lunar IceCube [148], LunaH-Map [149], SkyFire [150], NEAScout [151], CuSP [152], BioSentinel [94], OMOTENASHI [153], EQUULEUS [153], and ArgoMoon [153] (Table 1), and three additional 6U CubeSat missions will be selected through NASA's Cube Quest Challenge in 2017 to fly on EM-1 [154]. The CubeSats on EM-1 will demonstrate scientific and technological capabilities beyond LEO with an aim of ultimately opening deep space to CubeSat class missions as well as facilitating a future human exploration of deep space including a voyage to Mars.

CubeSats on EM-1 will immediately address multiple high value scientific questions such as locating and investigating the distribution of water and other volatiles on the moon, and exploration of the lunar surface and radiation environment near the moon. In fact, 5 CubeSat missions on EM-1 specifically Lunar Flashlight, Lunar IceCube, LunaH-Map, SkyFire and OMOTENASHI will conduct lunar exploration. Lunar Flashlight, Lunar IceCube and LunaH-Map missions will look for water and other volatiles on the moon using different techniques thus providing a wealth of synergetic data. Lunar Flashlight CubeSat mission will utilize its near infrared lasers to illuminate the permanently shaded polar regions, and use the onboard spectrometer to measure surface reflection and composition [87,147]. In contrast, Lunar IceCube mission is not limited to the shaded regions, and it will use the Broadband InfraRed Compact High Resolution Explorer Spectrometer (BIRCHES) developed by NASA's Goddard Space Flight Center to look for water in ice, liquid, and vapor states and other volatiles as a function of time, latitude, and regolith age and composition from a highly inclined elliptical lunar orbit [148]. Whereas, LunaH-Map CubeSat will use two neutron spectrometers to map near-surface hydrogen (H) at exceptionally high spatial resolution of about 7.5 km/pixel from a low altitude polar orbit with the focus on the lunar South Pole. The mission will count the neutrons over a total of 141 orbits then the neutron count rates will be translated into hydrogen abundances and distributions in the top one meter of the lunar surface [149,155]. Overall, Lunar Flashlight, Lunar IceCube and LunaH-Map will significantly improve our knowledge about the quantity and distribution of water and other volatiles on the moon by producing high resolution maps, which will also help to strategize future landing missions or other advanced missions such as the Moon Village concept recently proposed by ESA [156].

Near-Earth Asteroid Scout (NEAScout) is a CubeSat reconnaissance mission to fly by an asteroid 1991VG although the final target might change based on the launch schedule [151]. The main science payload on NEAScout mission will be a multispectral camera to image the target at 10 m/pixel and 50 m/pixel resolutions for estimating the shape, spin rate, pole position, regional morphology, regolith properties, spectral class as well as characterizing local environment. The spacecraft will utilize cold gas propulsion for the initial maneuvers then the NEAScout's signature 86 m^2 solar sail will propel the spacecraft to its final destination over about two year journey [89,151,157]. Near-Earth asteroids have potentially significant value in terms of science, human exploration, potential hazardous effects as well as in situ resource utilization. Thus this low-cost robotic CubeSat mission will provide valuable data on small asteroids, which will facilitate future human exploration of deep space destinations such as asteroids and comets. Additionally, the other confirmed SkyFire and OMOTENASHI CubeSat missions on EM-1 will conduct surface exploration of the moon by utilizing low-cost CubeSats to advance our knowledge about the lunar surface [150,153]. EQUULEUS mission will investigate the radiation environment in the region of the space around Earth through imaging Earth plasmasphere as well as measuring the distribution of plasma surrounding the planet. Whereas, the ArgoMoon mission will take historical photos of the EM-1 as well as will provide data on the deployment of other CubeSats while operating near the Interim

Cryogenic Propulsion Stage (ICPS). ArgoMoon will also test optical communication link between the spacecraft and Earth [153]. The last two confirmed CubeSats on EM-1 are CuSP mission studying solar particles and magnetic fields in interplanetary space as well as assessing the feasibility of creating a network of "Space Weather Stations" [152] and BioSentinel mission conducting biological experiment in order to study the damage and repair of DNA in organisms in deep space [94]. A more detailed information about CuSP and BioSentinel CubeSat missions are provided in the subsequent sections.

MarCO (Mars Cube One) is another notable deep space CubeSat mission being developed at NASA Jet Propulsion Laboratory. MarCO mission will consist of two identical 6U CubeSats for supporting telecommunications relay during entry, descent, and landing of the InSight Mars lander originally scheduled to be launched in 2016 [86,158] although some technical issues delayed the launch until 2018 [159,160]. MarCO CubeSats will be deployed by a spring after InSight is separated from the upper stage then the twin CubeSats will navigate to Mars independent of the InSight satellite based on their onboard capabilities [158]. Once at Mars, UHF antenna on each MarCO CubeSat will point towards InSight and the surface from an altitude of 3500 km, whereas the high-gain X-band antenna on MarCO CubeSats will point towards Earth. The mission will be capable of transmitting data from InSight lander to MarCO CubeSats via UHF link and subsequently from MarCO to the Deep Space Network's 70 m dish on Earth via X-band link with twin CubeSats operating mostly in series. The X-band link can provide an 8 kbps data rates from Mars to Earth [158]. Another significant CubeSat mission includes INSPIRE, "The Interplanetary NanoSpacecraft Pathfinder In Relevant Environment", which is a deep space technology demonstration mission scheduled to be launched in 2017. The INSPIRE mission consists of two identical, three-axis-stabilized 3U CubeSats with a nominal mission lifetime of 3 months, and are expected to achieve an Earth-probe distance of $1.5x10^8$ km depending on the escape velocity since neither nanosatellite has any propulsion capabilities [88]. The main objective of the INSPIRE mission is to demonstrate that CubeSats are capable of operating, communicating, and navigating far beyond Earth thus enabling deep space missions for CubeSat class platforms. Additionally, the INSPIRE CubeSats will carry two science payloads including a 0.5U compact vector-helium magnetometer to quantify the fine structure of the solar wind and an imager for demonstrating the science utility of deep space CubeSat platforms [161].

In summary, recent developments in CubeSat capabilities spurred increasing interest in deep space CubeSat mission concepts and already at least 15 CubeSat missions are scheduled to be launched within the next two years. It is expected that the performance of CubeSats will be demonstrated in deep space as soon as in 2017 or 2018 thus opening up new fascinating possibilities for future low-cost CubeSat mission. It is envisioned that sophisticated exploration architectures could possibly be developed by utilizing small spacecraft capabilities [162], thus allowing to answer high value questions as well as potentially reducing the usual decade long cycle of interplanetary missions with a fraction of the budget of a traditional deep space mission. Deep space CubeSats could be utilized for in situ exploration of planetary atmospheres, surfaces, asteroids as well as any unexplored and precarious regions although several distinctive challenges intrinsic to deep space missions such as strong radiation environments, thermal control, long distance communication, and high performance propulsion requirements need to be addressed in order to enable deep space CubeSat missions.

4.3. Heliophysics: space weather

Space weather can have detrimental effect on vital technologies both in space and on the ground including satellites, telecommunications, navigation, electrical power transmission, commercial aviation as well as has major health implications for humans in space, particularly during future deep space exploration. Thus space weather can cause significant damage to modern-day high-tech economies and the need for better understanding and predicting the space weather effects will only increase as our society relies on ever increasing high-tech infrastructures vulnerable to different space weather phenomena [163]. Even though numerous CubeSat missions carried space weather sensors starting from the early years of CubeSat developments most of them did not generate scientifically valuable results close to traditional spacecraft as was also highlighted by Selva and Krejci [15]. Specifically, this survey identified that relatively high performance CubeSat missions for space weather research started launching only during the last 5–6 years when US National Science Foundation (NSF) started to sponsor several nanosatellite missions for space weather studies [164].

The first space weather nanosatellite mission funded by the NSF CubeSat-based Space Weather and Atmospheric Research Program was Radio Aurora Explorer (RAX) mission consisting of two 3U CubeSats named RAX-1 and RAX-2 developed at the University of Michigan in a collaboration with SRI International. The RAX-1 nanosatellite was launched into a LEO circular orbit in 2010 [165] while the RAX-2 was launched into a LEO elliptical orbit in 2011 [166]. The primary mission objective was to investigate the formation and distribution of natural ionospheric plasma turbulence, which can significantly incapacitate the performance of the space based navigation and communication systems, by using ground-to-space bistatic radar experiment. The experiment uses globally distributed megawatt-class ground-based incoherent scatter radar stations to illuminate the plasma irregularities, while the CubeSat-based radar receiver records radar scatter from the irregularities in LEO. Thus, improving the state of space weather forecasting by gaining deeper insights into the formation, drivers and global spatial distribution of these ionospheric plasma irregularities [165,166].

The following are other notable launched space weather CubeSat missions: DICE nanosatellite mission, funded by the NSF CubeSat and NASA ELaNa programs and implemented at Utah State University, consists of two 1.5U CubeSats launched into LEO in 2011 to investigate the formation of the ionospheric Storm Enhanced Density (SED) bulge and plume by using two Langmuir probes for ionospheric in-situ plasma density measurements, electric field probes for in-situ DC and AC electric field measurements, and a magnetometer for in-situ DC and AC magnetic field measurements [71]. CSSWE mission is a 3U CubeSat funded by NSF and developed at the University of Colorado at Boulder, which was launched into an elliptical LEO in 2012 to measure the directional differential flux of high-energy electrons and protons by using a Relativistic Electron and Proton Telescope integrated little experiment (REPTile) energetic particle telescope [167]. The mission generated scientifically valuable dataset consisting of about 3.5 million points during approximately 2-year period [168]. CINEMA mission consists of four 3U CubeSats funded by NSF and Kyung Hee University in South Korea and developed in collaboration between University of California, Berkeley, Kyung Hee University and Imperial College London [164]. The first mission was launched into LEO in 2012 followed by CINEMA 2, CINEMA 3 in 2013, while CINEMA 4 is still in development. The science payload of the CINEMA mission consists of two high performance, low mass, and low power instruments including the Supra-Thermal, Electrons, Ions and Neutrals (STEIN) particle detector and a magnetoresistive magnetometer (MAGIC), which was implemented both inboard and on a deployed 1-meter stacer boom [169] for conducting high quality science observations of the Earth's ring current, charged particle precipitation and the magnetic field [164]. SENSE (SV-1, SV-2) is a two 3U CubeSat mission launched into LEO in 2013 to generate scientifically valuable ionospheric dataset for improving space weather forecast [170]. The science payload on SV-1 was a Compact Tiny Ionospheric Photometer (CTIP) to measure electron density profiles, total electron content, and the ionospheric structure, while the SV-2 spacecraft carried a Winds-Ion-Neutral Composition Suite (WINCS), which consists of Wind and Temperature Spectrometer (WTS), Ion Drift and Temperature Spectrometer (IDTS), Neutral Mass Spectrometer (NMS) and Ion Mass Spectrometer (IMS) to measure atmospheric and ionospheric density, neutral and ion composition, neutral and ion temperature, neutral winds, and ion drifts. Additionally, both nanosatellites carried Compact Total Electron Content Sensor (CTECS) and a micro dosimeter to measure ionospheric total electron content and GPS Radio Occultation for studying scintillation [72,170]. ExoCube is a 3U CubeSat funded by NSF and developed by a collaboration between California Polytechnic State University, Scientific Solutions, University of Wisconsin in Madison and the University of Illinois, and launched into LEO in 2015 [171] to measure global in-situ densities of various neutrals and ions including [O], [H], [He], [N2], [O+], [H+], [He+], [NO+] in the upper ionosphere and lower exosphere by using an Ion Neutral Mass Spectrometer (INMS) [172]. CADRE is a 3U space weather nanosatellite funded by NSF and lead by the University of Michigan and was launched into LEO in 2015. The main science payload of the mission is Wind Ion Neutral Composition Suite (WINCS) developed jointly by the Naval Research Laboratory (NRL) and NASA Goddard Space Flight Center (GSFC) [173] to measure the in-situ density, temperature and composition of the thermosphere as well as the neutral winds and ion flows in order to better understand the effects of large energy inputs on the thermosphere [174]. MinXSS is a two 3U nanosatellite mission developed at the University of Colorado at Boulder. The first MinXSS CubeSat was launched into LEO in 2015, whereas the second flight model MinXSS FM-2 is planned to be launched into a higher sun-synchronous polar orbit in 2016 [41]. The primary science objective of the mission is to better understand the energy distribution of solar soft X-ray emission and its impact on Earth's ionosphere, thermosphere, and mesosphere by using Amptek X123-SDD COTS X-ray Spectrometer [41].

CuSP 6U CubeSat is a breakthrough deep space weather mission being led by Southwest Research Institute and is planned to be launched onboard the first flight of NASA's Space Launch System (SLS) in 2018 [175]. The mission will study solar particles in interplanetary space by utilizing three science instruments including Suprathermal Ion Spectrograph (SIS) for detecting and analyzing low-energy solar energetic particles, Miniaturized Electron and Proton Telescope (MERiT) for counting high-energy solar energetic particles, and Vector Helium Magnetometer (VHM) for measuring the strength and direction of magnetic fields. CuSP mission will become a pathfinder demonstrating the possibility of creating a network of space weather stations based on a CubeSat standard [152].

In summary, the principal objectives of these CubeSat missions are to advance our knowledge about broader space weather phenomena and ultimately to improve our capabilities to better predict perilous effects of the space weather on critical infrastructures. Currently, both custom built and commercial-off-the-shelf high performance instruments such as particle detectors, mass spectrometers, X-ray spectroscopy, Langmuir probes, electric field probes, GNSS receivers, and magnetometers are readily available for space weather CubeSat missions with some instruments already having strong flight heritage. Moreover, the high performance space weather CubeSat missions still under development will further advance the state of the space weather prediction as well as will reinforce the functionality of CubeSat platforms as capable space weather systems, thus potentially enabling a future network of space weather stations based on CubeSat platforms. CubeSats already demonstrated their capability to conduct science quality space weather observations by either augmenting the capabilities of larger systems or by conducting targeted missions.

4.4. Astrophysics

Nanosatellite missions have been developed and launched for investigating a wide range of fundamental astrophysical processes central to better understanding the Universe and its evolution (Table 1). For instance, CXBN mission is a 2U sun-pointing, spinning spacecraft launched into LEO in 2012 with the main science objective of improving the precision of the cosmic X-Ray background measurements in the range of 30–50 keV by using a Cadmium Zinc Telluride (CZT) detector to gain deeper insights into the structure, origin, and evolution of the universe [176]. CXBN-2 is a follow-on mission to CXBN planned to be launched in 2016, which incorporates several enhancements based on the lessons learned from the CXBN mission given that the science payload of CXBN did not achieve nominal operation despite a successful in-orbit operation of the spacecraft bus [177]. Another launched CubeSat example includes S-CUBE, a 3U nanosatellite developed through a collaboration between Chiba Institute of Technology and Tohoku University and launched into LEO in 2015 [178]. The primary objective of the mission is a global observation of meteors from a low earth orbit for estimating the meteoroid size from the observed brightness, flux of meteors as well as compositions of meteors from emission from species, such as sulfur by using one camera to take visible images and three photomultiplier tubes (PMT) to observe UV emissions [179].

BRITE (BRIght Target Explorer) constellation is a group of notable nanosatellite missions conducting astrophysical research, although not confined to a CubeSat form factor nevertheless a significant development in nanosatellite capabilities. BRITE constellation consists of international nanosatellite missions from three different countries for exploring stellar structure and evolution of the most luminous stars and their interaction with the local environment. Total of six 7 kg nanosatellites based on Generic Nanosatellite Bus (GNB) platform with a size of $20\times20\times20\ cm^3$ were developed by Austria, Poland, and Canada with two nanosatellite contributions from each country [180,181]. BRITE-A, BRITE-U and BRITE-P1 nanosatellites were launched into LEO in 2013, whereas, BRITE-P2, BRITE-C1 and BRITE-C2 missions were launched in 2014 although BRITE-C2 mission was immediately lost due to a deployment failure, the spacecraft did not properly detach from the upper stage of the rocket [181]. The primary science payload on each nanosatellite is an optical telescope with an aperture of 3 cm for measuring the brightness and temperature variations of stars usually brighter than mag(V) ≈4 in red and blue colors [182]. The telescope has a field of view of approximately 24° thus enabling concurrent observation of up to around 15 bright stars. One of each nanosatellite pairs from every country focuses on the blue (390–460 nm) region of the spectrum (BRITE-A, BRITE-P1, BRITE-C2) while the second nanosatellite focuses on the red (550–700 nm) region of the spectrum (BRITE-U, BRITE-P2, BRITE-C1). The main mission goal of BRITE constellation is to better understand the life cycles of the brightest stars in the sky through high-precision differential photometry and astroseismology [180,182].

Several other CubeSat missions for conducting astrophysical exploration are currently in development including ASTERIA, a 6U CubeSat mission in development at NASA Jet Propulsion Laboratory and is scheduled to be launched in 2017 [183]. The primary objective of the mission is to look for transits of identified RV planets and conduct high cadence stellar photometry over long durations by using a CMOS imager. The precise stellar photometry data will be utilized to investigate flares and stellar activity. Additionally, the technological demonstration aspect of ASTERIA CubeSat is to achieve pointing capability of better than 10 arcseconds [184]. HaloSat is another NASA funded 6U CubeSat mission in development at the University of Iowa and is planned to be launched in 2018 [185]. The primary science objective of the HaloSat mission is an exploration of a hot galactic halo in the Milky Way galaxy through mapping of the emission lines of oxygen in order to constrain its distribution and geometry by using three identical commercial-off-the-shelf Amptek X-ray detectors. Thus, the mission will significantly enhance our knowledge about the quantity and distribution of hot gas in the Milky Way galaxy as well as solar wind charge exchange interactions within the solar system. Ultimately, HaloSat mission will answer the question: "Is there a massive, extended, hot halo around the Milky Way?" thus helping to resolve the cosmological missing baryon problem [185,186]. The last example includes PicSat, which is a 3U CubeSat in development at LESIA, Observatoire de Paris and is scheduled to be launched into LEO with an altitude of 620 km in 2017 [187]. The primary objective of the mission is to detect the Beta Pictoris b transit predicted to happen between mid 2017 and mid 2018 by using a 5 cm telescope in order to determine the radius of the planet, the Hill Sphere and characterize inhomogeneities in the disk [188,189].

In summary, the CubeSat utilization for astrophysical exploration have been limited with only a handful of missions launched or currently in development and most of the missions use small telescopes or some sort of detectors such as X-ray as their main science payload. However, the early missions demonstrated the strong potential of small satellites for conducting high quality astrophysical missions. Although, it is hard to imagine CubeSats being able to completely replace the large traditional spacecraft, they unquestionably can complement the larger missions, fill some specific niches or become a gap filler between large traditional missions. Thus CubeSats have the potential to substantially enhance the overall value of the mission as well as to conduct innovative astrophysical research such as long term observation of targeted stars and transiting planets, perform interferometry and reduce the risk of future large missions by testing technologies at a fraction of the cost of traditional missions. Additionally, CubeSats could also enable high-risk high-value missions such as the development of synthetic apertures.

4.5. Spaceborne in situ laboratory

This section explores the missions conducting scientific experiments in space by utilizing CubeSat platforms as a cutting-edge science laboratory, this category of missions is garnering significant interest over the last decade as evidenced by increasing number of missions (Table 1). To date, five CubeSat missions were launched and at least another six missions are in development that will utilize the spacecraft platform as an onboard laboratory for conducting high value scientific experiments in space. Launched missions include 3U GeneSat-1 [190], PharmaSat 1 [191], O/OREOS [73], and SporeSat-1 [92,192] CubeSats all conducting biological science experiments investigating wide range of questions such as better understanding overall effects of microgravity and space radiation on different biological organisms, their metabolism, the effectiveness of anti-fungal agents as well as assessing the viability of microorganisms and the stability of organic molecules in the space environment. Another launched spacecraft that conducted onboard experiment was 1U Lambdasat [193], which studied graphene in space environment for understanding the effects of radiation on graphene properties, 1U ³Cat-1 mission, still in development, will also test a graphene device (in particular a Graphene Field Effect Transistor (GFET)) in space conditions, the experiment will measure the GFET performance and degradation at several phases of the mission in order to understand the effects of space environment on these novel devices [194].

Several missions currently under development are envisioned to open up new frontiers for CubeSat onboard science capabilities. EcAMSat [93] and BioSentinel [94] are two notable 6U CubeSat missions currently being developed at NASA Ames Research Center for conducting biological studies in space. EcAMSat mission will investigate microgravity effects on the dose-dependent antibiotic response and resistance of wildtype and mutant strains of uropathogenic E. coli. The mission is based on the PharmaSat 1 hardware launched in 2009 although the biological payload will be changed from yeast on PharmaSat 1 to E. Coli on EcAMSat. This change from eukaryote to bacteria enables testing of the antibiotic Gentamicin on wild type uropathogenic E. coli as well as on a gene knock out mutant in the space environment [93]. Whereas, the 6U BioSentinel CubeSat mission will make an exceptional progress in CubeSat capabilities by going beyond LEO. BioSentinel will be the first mission in more than four decades to conduct direct biological experiment beyond LEO during its 12–18 month mission lifetime. The CubeSat mission will investigate the damage and repair of DNA in a biological organism as well as will compare it to onboard radiation observations [94]. BioSentinel mission will be a vital step towards better understanding the deep space environment and its effects on living organisms thus potentially enabling future long term human exploration of deep space.

Q-PACE is a 2U CubeSat being developed at the University of Central Florida to investigate fundamental properties of low-velocity (< 10 cm/s) particle collisions in microgravity [195]. The CubeSat mission will house a collision test cell as well as a number of reservoirs containing particles of meteoritic chondrules, dust, dust aggregates, and larger spherical monomers to conduct several different experiments in order to better understand accretion in the protoplanetary disk and early stages of planet formation [195]. The 3U CubeSat mission AOSAT [196] is in development at Arizona State University to investigate planet formation and asteroid surface properties. The spacecraft is divided into 3×1U compartments where the central 1U chamber will house all spacecraft subsystems while the outer two 1U payload chambers will contain meteorite fragments and dust particles. One of the payload chambers could be used to investigate the primary accretion process and the second payload chamber could be used to investigate the asteroid-like regolith properties [197]. During the primary accretion study the attitude control subsystem will spin stabilize the CubeSat thus creating a realistic primary accretion experiment by using representative materials in a representative environment over long timeframes. Whereas, the properties of asteroid regolith will be investigated by simulating surface conditions on asteroids through artificial gravity similar to a 1 km size asteroid produced by spinning the spacecraft on its minor axis. Thus, with a modest budget the AOSAT CubeSat mission could answer essential questions related to the early planet formation as well as making the first steps towards future asteroid exploration and sample return missions [196,197]. Another in development CubeSat concept featuring an onboard science experiment includes ChargerSat-2 CubeSat [198] proposed by University of Alabama in Huntsville to investigate heat transfer properties of nucleate boiling in microgravity, although no recent progress was found on this particular mission concept.

In summary, CubeSat platforms have tremendous potential to be utilized as sophisticated spaceborne science laboratories for conducting innovative research in wide range of areas such as biomedical sciences, materials sciences, physical sciences and plant sciences under space radiation and microgravity conditions over extended periods. Even though, it is possible to simulate space radiation effects in a laboratory on Earth, the real space exposure could provide significantly more information, whereas alternatives for conducting microgravity experiments include drop towers, parabolic flights or experiments on International Space Station (ISS). However, drop towers or parabolic flights provide only very short periods of microgravity conditions and cannot realistically simulate numerous real world phenomena [197]. Although, ISS is a valuable platform for conducting research it has limited capacity as well as very strict regulations, delicate legal framework and getting a research project onto ISS could be very expensive and time consuming endeavor [199] thus, in most cases it would be out of reach for many research groups as well as long durations of getting a research project to ISS precludes frequent innovative iterations and upgrades. CubeSat platforms could be an excellent alternative for conducting research in space with potentially much faster reiteration cycle at relatively low cost thus enabling much wider access to space. Moreover, SpacePharma [200] company already started to commercialize this idea by offering CubeSat platforms for microgravity research, SpacePharma's DIDO-1 and DIDO-2 3U CubeSats scheduled to be launched in 2016 will be the first commercial nanosatellites for microgravity research [200,201]. Even though, spaceborne in situ laboratories based on CubeSat platforms demonstrated their value several major challenges still need to be addressed such as limited downlink rates, which may preclude high-definition imaging or video recording as well as long launch delays after CubeSat integration with the launch vehicle [23]. The delays of weeks or months will create severe challenges for complex biological payloads as well as for preventing the degradation of drugs and reagents to be utilized in the scientific experiments.

4.6. Technology demonstration

CubeSats originally started as cutting-edge educational platforms then rapidly transformed into technology demonstration tools as well as more recently started to be increasingly exploited for scientific and commercial purposes. CubeSats allow educational institutions to teach challenging engineering concepts such as understanding the interdependent subsystems and how they fit into an integrated complex systems during the design, development and testing of small spacecraft missions by using hands-on educational approach. CubeSats give students a unique opportunity to be involved in a real and stimulating space mission that will actually be launched into space during their studies, given the short development time of CubeSat missions it could be an end-to-end endeavor starting from mission formulation to mission implementation for most of the students. Unquestionably, CubeSat programs have tremendous educational value in terms of developing essential skills and hands-on experience in science, engineering, and management required to succeed in science and technology professions, as well as to attract and retain more students and improve the involvement of underrepresented groups in science and technology fields [23,164].

Technology demonstration is another area that CubeSats are being extensively exploited since the early years of the development. Generally, the technology demonstration on CubeSat platforms can be divided into two categories including demonstration of technologies intended to be utilized on larger, expensive missions and demonstrations of enabling technologies anticipated to be primarily utilized on CubeSat class missions. An example of large satellite mission enabling technology demonstration includes GRIFEX, a 3U CubeSat with the primary goal of validating the functionality of all digital in-pixel high frame rate read-out integrated circuit for enabling a future Geostationary Coastal and Air Pollution Events (GEO-CAPE) mission concept [202]. However, a large fraction of the technology demonstration missions is dedicated to enabling technologies for sophisticated CubeSat missions. Several notable CubeSat technology demonstration missions are listed in Table 1, although there are hundreds of launched and planned technology demonstration missions but for the practicality of the study only several missions with significant technological advancements were explored further in this section. The high value developments for CubeSats include several key enabling technology areas such as high-speed communications, precision attitude determination and control, propulsion, precise thermal control, and high performance miniaturized science instruments. These enabling technologies along with other critical subsystems are central to the evolution of CubeSats into more capable space platforms that could conduct science quality observations and ultimately improve both the commercial and science value of CubeSat missions.

Several missions already started to address these critical CubeSat constrains, for example, ISARA 3U CubeSat is demonstrating a high gain Ka-band reflectarray antenna integrated into solar arrays to enable downlink data rates of over 100 Mbps [76], while the three 1.5U AeroCube OCSD CubeSat mission is demonstrating high-speed optical communication capability for achieving data rates of about 500 Mbps and even possibly approaching Gbps rates [203]. These data rates are orders of magnitude higher than currently achievable over UHF or S-band communication systems commonly used on CubeSat platforms, thus potentially opening numerous data intensive missions to CubeSats. Precision attitude determination and control is another important technology area that experienced significant progress. For instance, ASTERIA 6U CubeSat mission in development at NASA Jet Propulsion Laboratory is aiming to achieve arcsecond-level line of sight pointing error and highly stable focal plane temperature control, thus potentially enabling precision photometry for investigating stellar activities, transiting exoplanets, and additional space phenomena [184]. Another enabling technology is CubeSat compatible propulsion systems, which is a very active area and in addition to traditional propulsion systems several innovative propulsion systems such as solar sail and electrodynamic tether propulsion are gaining increasing interest. Already, several missions such as LightSail-A, B [57] and NanoSail-D2 [58] 3U CubeSats are advancing the state of the art of solar sailing technology for CubeSat platforms, whereas the TEPCE-A, B [204] CubeSat mission is designed to demonstrate electrodynamic tether propulsion in space by using two identical 1.5U CubeSats attached to each other by one kilometer long electrically conducting tether.

One of the key enabling technologies for CubeSats is the availability of high performance miniaturized instruments compatible with CubeSat platforms. Indeed, over the last several years significant work has been done in this area in order to miniaturize heritage instruments or to develop novel CubeSat specific instruments (Table A1). Several CubeSat missions currently developing sophisticate payload capabilities include the Compact Infrared Radiometer in Space (CIRiS) is an uncooled imaging infrared (7.5–13 μm) radiometer designed for high radiometric performance from LEO on a CubeSat platform [205], CubeSat Infrared Atmospheric Sounder (CIRAS) is a mission intended to develop a CubeSat compatible instrument capable of producing the temperature and water vapor profile measurements in the lower troposphere comparable to NASA's Aqua mission and NASA/NOAA Joint Polar Satellite System [206], and Precipitation Profiling Radar in a CubeSat (RainCube) is a 6U mission in development at NASA Jet Propulsion Laboratory and it will be the first active radar on a CubeSat class spacecraft [102]. Additionally, several custom-built and commercial-off-the-shelf high performance instruments such as particle detectors, mass spectrometers, neutron spectrometers, X-ray spectroscopy, Langmuir probes, electric field probes, GNSS receivers, magnetometers and imagers are readily available.

Furthermore, over the past several years significant technology development and demonstration occurred for enabling formation flying mission concepts [18]. A few notable missions demonstrating some kind of formation flying or inter-satellite operation capabilities include CANX-4 & 5 [207], Nodes-A, B [208], VELOX-II [209], CPOD-A, B [210], DelFFi-Delta, Phi [211], RANGE-A, B [212], CANYVAL-X [213], SAMSON-A, B, C [214], TEPCE-A, B [204], AMODS [215], and AAReST [216] (Table A1). Formation flying could potentially enable mission architectures currently impractical with traditional approaches such as, for example, AAReST mission is planning to demonstrate an autonomous, in-orbit assembly of a large space telescope using multiple mirror elements by launching two 3U "MirrorSats" and one central 15U "CoreSat" [216] or AMODS mission demonstrating in-orbit inspections on conventional spacecraft by using one self-propelled transport CubeSat (BRICSat) to deliver one of several "repair" CubeSats (RSats) with manipulable arms to spacecraft for diagnostic and maintenance services designed to extend the life of that satellite [215] or CANYVAL-X mission demonstrating distributed virtual telescope by flying two nanosatellites in a precise formation along an inertial line-of-sight [213]. Formation flying capabilities could enable innovative distributed architectures based on CubeSats such as fractioned spacecraft [217], constellations [218], swarms [218], and federated space systems [219]. Fractionated spacecraft are the disaggregation of a monolithic satellite into free-flying subsystems, which are particularly interesting in the framework of CubeSats (Fig. 5). The disaggregation enables decoupling of system functions, thus allowing the deployment of individual sensors independent from each other, and in case of failures or mission goal

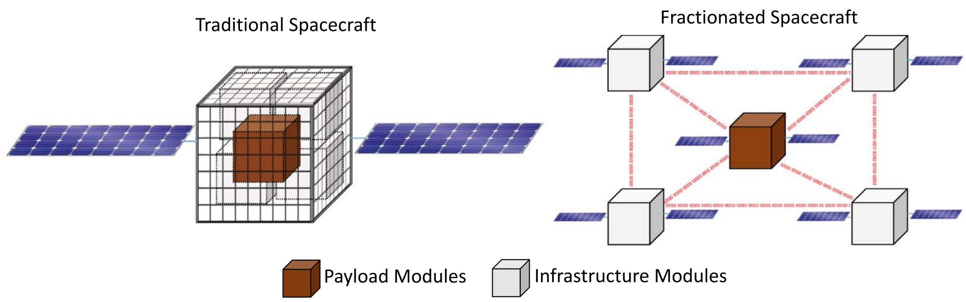

Fig. 5. Block diagram comparing traditional and fractionated spacecraft.

changes a particular subsystem or a payload could be replaced or added [220]. For example, a CubeSat could be used to add a new band or to replace a particular subsystem in already launched systems, which will potentially extend the mission lifetime and improve the overall system value for a relatively small investment. Contrary, monolithic satellites normally need to be completely replaced in these circumstances requiring much larger investment [217]. The low cost and short development cycle of CubeSat class missions leveraged by robust formation flying capabilities could enable mission architectures when multiple CubeSats operate together to augment the functionality of traditional spacecraft or to create novel applications such as interferometry or large network of sensors for multipoint sensing with high temporal and spatial resolutions as well as high spectral resolution. Additionally, CubeSat missions could be utilized as telecommunications relay for future deep space exploration [221], such as the planned MarCO mission to Mars [222]. Furthermore, several missions are also exploring controlled atmospheric re-entry and deorbiting capabilities of CubeSat platforms, examples include TechEdSat-3, 4 [223,224], QARMAN [225], and CanX-7 [226] missions. These technologies could enable future CubeSat missions with landing capabilities for exploring planetary surfaces, atmospheres, as well as it could be used as a fast and affordable method for sample return from in-orbit platforms such as the International Space Station. Whereas, deorbiting capabilities will help to comply with orbital debris mitigation requirements [46].

In summary, technology demonstration will continue to command significant development efforts in the near future since the CubeSat as a technology is still very much in its infancy. Thus new technological breakthroughs will continue to propel a wide utilization of CubeSat platforms both for scientific and commercial purposes. Additionally, CubeSats will most likely continue to be used to validate enabling technologies intended to be used on large, expensive space missions. The technology advancements will continue to drive the space industry to some equilibrium state when small and large satellites complement each other for increasing the return on an investment. For example, CubeSats will excel at low cost dedicated missions, high-risk high-value missions, or multi-point sensing missions, while large traditional satellites will continue to be used for missions requiring complex multi-instrument investigations as well as some hybrid mission architectures will emerge when small and large satellites work together to substantially enhance the mission capabilities and value.

5. Conclusion

Even though, CubeSats are now gradually being utilized for scientific purposes, the initial missions demonstrated that CubeSat platforms could potentially be used to conduct high quality science and enable new missions in addition to being used for spaceborne applications. After about fifteen years and hundreds of launched missions it is undisputable that CubeSats are more than just superb educational or low-cost technology demonstration platforms. CubeSats are capable satellites offering formidable prospects for conducting real science missions as well as high value commercial missions at a fraction of the cost of traditional spacecraft, and in 2–3 years CubeSats will most likely reach as far as Mars and Moon. It is unlikely that CubeSats will be able to completely replace large traditional spacecraft, they can unquestionably complement larger missions, fill specific niches or become a gap filler between large traditional missions as well as reconsidering the space exploration in the framework of CubeSats will enable novel and revolutionary mission concepts in the future. CubeSats could excel at targeted missions, multipoint observations and high-risk high-value missions as well as could augment the capabilities of traditional large science missions by combining several low-cost CubeSat platforms. Additionally, their low cost and fast development cycle could potentially enable exceptional scientific missions based on distributed space system architectures such as fractionated spacecraft, satellite swarms and constellations for achieving unprecedented temporal and spatial coverage as well as for creating new breakthrough capabilities. CubeSats could potentially enable a future network of space weather stations, which will advance our knowledge about broader space weather phenomena and ultimately to improve our capabilities to better predict perilous effects of the space weather on critical infrastructures. Additionally, CubeSats could be utilized for in situ exploration of planetary atmospheres, surfaces, asteroids and any unexplored and precarious regions as well as could potentially reduce the usual decade long cycle of interplanetary missions with a fraction of the budget of a traditional deep space mission. CubeSats could be also used for long term observation of targeted stars and transiting planets, performing interferometry as well as developing synthetic apertures. However, several distinctive challenges intrinsic to deep space missions such as strong radiation environments, thermal control, long distance communication, and high performance propulsion requirements need to be addressed in order to enable deep space CubeSat missions. Furthermore, CubeSat platforms have demonstrated a tremendous potential to be utilized as sophisticated spaceborne science laboratories for conducting innovative research in wide range of areas such as biomedical sciences, materials sciences, physical sciences and plant sciences under space radiation and microgravity conditions. CubeSat platforms could be an excellent alternative to International Space Station (ISS) for conducting research in space with potentially much faster reiteration cycle at a relatively low cost. Despite the potential high value of spaceborne CubeSat science laboratories several major challenges still need to be addressed such as limited downlink rates, which may preclude high-definition imaging or video recording as well as long launch delays after CubeSat integration with the launch vehicle, which will create severe challenges for complex biological payloads as well as for preventing the degradation of drugs and reagents. Further CubeSat technological breakthroughs will continue to propel a wide utilization of CubeSat platforms both for scientific and commercial purposes as well as will continue to drive the space industry to some equilibrium state when small and large satellites complement each other to increase the return on the investment.

Appendix A

See Table A1.

Table A1
List of all analyzed CubeSat missions with the name, size, leading organization, primary objectives and launch status along with corresponding references.

Mission ID	Size	Organization	Objectives	Launch	Ref.
Earth Science and Spaceborne Applications					
QuakeSat	3U	Stanford University, QuakeFinder, LLC	Detect extremely low frequency magnetic field signals associated with large earthquakes by using AC magnetometer	2003	[227]
ION	2U	University of Illinois at Urbana-Champaign	Measure molecular Oxygen airglow emissions from the Earth's mesosphere using a 760 nm photometer. [Launch failure]	2006	[228]
CanX−2	3U	University of Toronto	Measure the total electron and water vapor content as a time-varying function of altitude by a GPS occultation as well as greenhouse gases by an Argus atmospheric spectrometer	2008	[45]
CanX−6	6.5 kg GNB	University of Toronto, COM DEV Ltd.	Detect Automatic Identification System (AIS) signals transmitted by maritime vessels	2008	[127]
SwissCube	1U	Ecole Polytechnique Fédérale de Lausanne (EPFL)	Observe oxygen emission at 767 nm to characterize the airglow intensity as a function of observation angle, altitude, latitude and local time	2009	[229]
PRISM	8.5 kg	University of Tokyo	Acquire Earth images with better than 30 m resolution by using an extended optical system	2009	[230]
AISSat−1AISSat−2AISSat−3	7 kgGNB	University of Toronto, Norwegian Space Center	Detect Automatic Identification System (AIS) signals transmitted by maritime vessels	20102014 in devel.	[128, 129]
SRMSAT	10.9 kg	Sri Ramaswamy Memorial University	Monitor carbon dioxide and water vapor levels in atmosphere by observing absorption spectrum in an infrared range of 900 nm −1700 nm by using a grating Spectrometer	2011	[117]
AENEAS	3U	University of Southern California	Track cargo containers over the open ocean with a 1-watt WiFi-like transceiver	2012	[133]
Ho'oponopono 2 (H2)	3U	University of Hawaii at Manoa	Perform radar calibration by using a C-band transponder and high-accuracy GPS payload	2013	[134]
Firefly	3U	NASA Goddard Space Flight Center	Explore the relationship between lightning and Terrestrial Gamma Ray Flashes (TGFs) by using a Gamma Ray Detector, a Very Low Frequency receiver and photometers	2013	[125]
WNISAT 1	10 kg	Weathernews Inc., AXELSPACE	Monitor sea ice in the Arctic Sea by using a camera with blue, green, red and near infrared bands as well as roughly estimating the density of atmospheric CO_2 using a laser	2013	[231]
MicroMAS−1	3U	Massachusetts Institute of Technology	Study convective thunderstorms, tropical cyclones, and hurricanes by a 9-channel passive microwave spectrometer observing near the 118.75 GHz oxygen absorption line. [No payload data due to a transmitter failure]	2014	[112]
RACE	3U	University of Texas at Austin, NASA Jet Propulsion Laboratory	Measure the liquid water path and precipitable water vapor that is pertinent to the water cycle and Earth energy budget by using a microwave radiometer that primarily observes near the 183 GHz water vapor line. [Launch failure]	2014	[232]
Perseus-M1 Perseus-M2	6U	Aquia Space, Dauria Aerospace	Detect Automatic Identification System (AIS) signals transmitted by vessels	2014	[130]
ExactView 9 (EV9)	5.5 kg GNB	ExactEarth Inc., University of Toronto	Detect Automatic Identification System (AIS) signals transmitted by vessels	2015	[132]
AAUSAT4	1U	Aalborg University	Detect Automatic Identification System (AIS) signals transmitted by vessels	2016	[131]
GHGSat-D (Claire)	15 kg	GHGSat Inc., University of Toronto	Measure carbon dioxide and methane emissions from selected targets with a spatial resolution of better than 50 m by using an advanced miniature hyperspectral short-wave infrared (SWIR) imaging spectrometer	2016	[233]
Aoxiang-Sat	12U	Northwestern Ploytechnical University, China	Detect the skylight polarization patterns and measure gravity	2016	[234]
SathyabamaSat	2U	Sathyabama University, Chennai, India	Measure the levels of water vapor, carbon monoxide, carbon dioxide, methane and hydrogen fluoride by using Argus 1000 multispectral infrared spectrometer	2016	[118]
^{3}Cat−2	6U	Universitat Politécnica de Catalunya	Perform ocean and ice altimetry and scatterometry for sea state determination, soil moisture measurements, and biomass monitoring by using Global Navigation Satellite Systems Reflectometry (GNSS-R)	2016	[109]
RAVAN	3U	The Johns Hopkins University Applied Physics Laboratory	Measure top-of-the-atmosphere Earth-leaving fluxes of total and solar-reflected radiation by using a small, accurate radiometer that is a pathfinder for a possible future Earth radiation budget constellation	In Devel.	[123]
HARP	3U	University of Maryland Baltimore County	Characterize the micro physical properties of aerosols and clouds for narrowing uncertainties in climate change by	In Devel.	[122]

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Table A1 *(continued)*

Mission ID	Size	Organization	Objectives	Launch	Ref.
			using a hyperangular imaging polarimeter		
IceCube (Earth−1)	3U	NASA Goddard Space Flight Center	Remote sensing of global cloud ice from space with 883 GHz submm-wave receiver	In Devel.	[124]
MicroMAS-2A MicroMAS-2B	3U	Massachusetts Institute of Technology	Two 3U CubeSats equipped with a 12-channel passive microwave spectrometer providing imagery near 90 and 206 GHz, temperature sounding near 118 GHz, and moisture sounding near 183 GHz	In Devel.	[113]
MiRaTA	3U	Massachusetts Institute of Technology	Demonstrate advanced atmospheric remote sensing capabilities by using V- and G-band radiometers (52–58 GHz, 175–191 GHz, and 203.8–206.8 GHz), and a compact GPS radio occultation (GPS-RO) sensor	In Devel.	[108]
EON-MW	12U	Massachusetts Institute of Technology	Scanning 22-channel from 23 to 183 GHz high-resolution microwave spectrometer to provide data continuity with the existing AMSU and ATMS microwave sounders	In Devel.	[113]
TROPICS Constellation	3U	Massachusetts Institute of Technology	12 identical 3U CubeSats equipped with a 12-channel passive microwave spectrometer providing imagery near 90 and 206 GHz, temperature sounding near 118 GHz, and moisture sounding near 183 GHz from 3 low-Earth orbital planes with about 30-min revisit	In Devel.	[114]
PolarCube	3U	University of Colorado at Boulder	Perform tropospheric temperature sounding by using a passive microwave spectrometer with 8 channels centered around the 118.75 GHz oxygen emission line as well as map sea ice/ice-free regions over polar oceans	In Devel.	[115]
TBEx-1TBEx-2	3U	SRI International, University of Michigan	Study how the dynamics and processes in the troposphere can cause variability in the upper atmosphere and ionosphere by using tri-frequency radio beacons and a cluster of diagnostic sensors on five islands in Pacific	In Devel.	[235]
PICASSO	3U	Belgian Institute for Space Aeronomy	Study ozone distribution in the stratosphere, the air temperature profile up to the mesosphere, and the electron density and temperature in the ionosphere by a sweeping Langmuir probe and a visible and near-infrared hyper-spectral imager	In Devel.	[121]
LAICE	6U	University of Illinois at Urbana-Champaign	Understand how atmospheric gravity waves generated by weather systems in the lower atmosphere propagate and deliver energy and momentum into the mesosphere, lower thermosphere, and ionosphere	In Devel.	[236]
PARIKSHIT	2U	Manipal Institute of Technology, India	Image Earth in the wavelength range of 7.5–13.5 μm by using an uncooled microbolometer thermal camera as well as test an electrodynamic tether for deorbiting	In Devel.	[237]
Aalto−1	3U	Aalto University	Conduct Earth Observation by using a miniature spectral imager and measure the flux of > 700 keV electrons and > 10 MeV proton by a particle detector	In Devel.	[238]
SeaHawk-1 SeaHawk-2	3U	University of North Carolina Wilmington, Clyde Space Ltd	Perform optical and near-IR observation of ocean surface for sustained, high spatial and temporal resolution information about the surface ocean processes	In Devel.	[239]
CIRiS	6U	Ball Aerospace & Technologies Corp.	Uncooled imaging infrared (7.5–13 μm) radiometer designed for high radiometric performance for land and water resource management, research, and modeling	In Devel.	[119]
CIRAS	6U	NASA Jet Propulsion Laboratory	Acquire hyperspectral infrared atmospheric radiances for retrieval of temperature and water vapor in the lower troposphere with a performance similar to traditional spacecraft	In Devel.	[120]
RainCube	6U	NASA Jet Propulsion Laboratory	Validate a Ka-band precipitation radar for climate science and weather forecasting. It will be the first active radar on a CubeSat	In Devel.	[102]
TEMPEST-D	6U	Colorado State University	Demonstrate a 5-frequency millimeter-wave radiometer at 89, 165, 176, 180 and 182 GHz to reduce the risk for a future constellation of five 6U CubeSats for global observation of time evolution of precipitation	In Devel.	[116]
DUSTIE	3U	Virginia Tech	Determine the global distribution of cosmic smoke in the atmosphere at an altitude of 40–90 km by using a camera to image the Sun at 0.42 μm during sunrise and sunset	In Devel.	[240]
GOSTE−1	3U	University of Hawaii at Manoa	Understand tropical cyclogenesis by using GNSS radio occultation system to improve estimates of the potential intensity of developing tropical cyclones and their intensity predictions as well as help to test general circulation model predictions	In Devel.	[106]
CONASAT-1 CONASAT-2	8U	INPE - National Institute For Space Research	At least 2 spacecraft constellation to gather environmental data such as rain volume, temperature, humidity, air pollution, ocean stream collected by remote ground platforms and retransmit them to the mission center	In Devel.	[136]
OPAL	3U	Utah State University	Profile the thermosphere temperature from 90 to 140 km altitude by observing the daytime O2 A-band emission (758 – 768 nm) by a high resolution imaging spectrometer	In Devel.	[241]
ARMADILLO	3U	University of Texas, Austin	Study the submillimeter space debris size range and	In Devel.	[107]

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Table A1 *(continued)*

Mission ID	Size	Organization	Objectives	Launch	Ref.
			provide in-situ data collection using a piezoelectric dust detector as well as conduct ionospheric GPS radio occultation		
Buccaneer	3U	UNSW Australia, DSTO	Provide performance calibration for Jindalee Over-the-Horizon Radar Network (JORN)	In Devel.	[135]
TRYAD-1 TRYAD-2	3U	University of Alabama in Huntsville, Auburn University	Measure the beam profiles and tilts of Terrestrial Gamma-ray Flashes (TGFs) using a pair of CubeSats separated by several hundred km in LEO to advance our understanding of this atmospheric phenomenon	In Devel.	[126]
QB50 Constellation	2U 3U	QB50 Project	Conduct multi-point in-situ atmospheric research within the lower thermosphere, between 200 and 380 km altitude by a network of 50 international University CubeSats	In Devel.	[137]
Flock Constellation	3U	Planet Labs Inc	Collect commercial Earth imagery with a resolution of 3–5 m on a global-scale	In Devel.	[105]
Landmapper-BC Constellation	6U	Aquila Space, Astro Digital	Collect daily commercial multispectral Earth imagery of arable and coastal areas worldwide with a resolution of 22 m in Green, Red, and NIR spectral bands	In Devel.	[130,139]
Landmapper-HD Constellation	16U	Aquila Space, Astro Digital	Collect commercial multispectral Earth imagery of arable and urban areas every four days with a resolution of 2.5 m in Blue, Green, Red, Red Edge, NIR spectral bands	In Devel.	[130,139]
Hera Constellation	12U	Hera Systems Inc.	Generate daily imagery and video of Earth at 1 m resolution by launching nine satellites	In Devel.	[140]
Lemur−2 Constellation	3U	Spire Global, Inc	Commercial constellation for GNSS-Radio Occultation and global AIS ship tracking	In Devel.	[138]
PlanetiQ Constellation	6U	PlanetiQ, LLC	Commercial constellation of 12 6U CubeSats entirely focused on weather, climate and space weather applications by using GPS Radio Occultation sensor	In Devel.	[141]
Deep Space Exploration					
Lunar Flashlight	6U	NASA Jet Propulsion Laboratory and Marshall Space Flight Center	Locating ice deposits in the moon's permanently shadowed craters, detecting composition, quantity, distribution, and form of water/H species and other volatiles	In Devel.	[147]
Lunar IceCube	6U	Morehead State University	Investigating the distribution of water and other volatiles as a function of time of day, latitude, and regolith age and composition from a highly inclined elliptical lunar orbit	In Devel.	[148]
LunaH-Map	6U	Arizona State University	Measure the bulk hydrogen content, up to a meter beneath the surface of the entire South Pole of the moon by using a neutron detector and producing the highest resolution to date	In Devel.	[149]
SkyFire	6U	Lockheed Martin	Performing a lunar flyby and taking infrared sensor data for surface characterization, remote sensing, and site selection as well as collecting data on thermal environments	In Devel.	[150]
NEAScout	6U	NASA Marshall Space Flight Center, Jet Propulsion Laboratory	NEA Scout is a reconnaissance mission to gather data at an asteroid representative of potential future human mission destinations	In Devel.	[151]
OMOTENASHI	6U	JAXA, University of Tokyo	Demonstrate the technology for CubeSat exploration of the lunar surface. It will also measure the radiation environment near the moon as well as on the lunar surface	In Devel.	[153]
EQUULEUS	6U	JAXA, University of Tokyo	Study the radiation environment in the region of space around Earth by imaging Earth's plasmasphere and measuring the distribution of plasma that surrounds the planet	In Devel.	[153]
ArgoMoon	6U	Argotec, Italian Space Agency	Take historical photos of the EM−1, provide mission data on the deployment of other Cubesats and test optical communication capabilities between the CubeSat and Earth	In Devel.	[153]
MarCO	6U	NASA Jet Propulsion Laboratory	Two 6U CubeSats supporting telecommunications relay during entry, descent, and landing of InSight Mars mission	In Devel.	[222]
INSPIRE	3U	NASA Jet Propulsion Laboratory	Two 3U CubeSats carrying a helium-vector magnetometer and an imager payloads for opening deep space to CubeSats	In Devel.	[161]
Heliophysics: Space Weather					
RAX-1RAX-2	3U	University of Michigan, SRI International	Ground-to-space bistatic radar experiment studying the formation of plasma irregularities in ionosphere	20102011	[165,166]
DICE-1DICE-2	1.5U	Utah State University	Investigate the formation of the ionospheric Storm Enhanced Density (SED) bulge and plume by using Langmuir probes, electric field probes, as well as magnetometers	2011	[71]
CSSWE	3U	University of Colorado at Boulder	Measure the directional differential flux of high-energy electrons and protons by a miniaturized energetic particle telescope	2012	[167]
CINEMA	3U	University of California, Berkeley	Perform critical space weather measurements by STEIN particle detector and by inboard and 1 m boom-deployed MAGIC magnetoresistive magnetometer	2012	[169]
CINEMA 2 CINEMA 3	3U	Kyung Hee University	Identical to CINEMA mission, 4 CubeSat constellation	2013	[164]

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Table A1 *(continued)*

Mission ID	Size	Organization	Objectives	Launch	Ref.
			developed by University of California, Berkeley, Kyung Hee University of Seoul, and Imperial College London		
SENSE SV1 SENSE SV2	3U	US Air Force	Investigate space weather by Compact Tiny Ionospheric Photometer on SV−1, Winds-Ion-Neutral Composition Suite (WINCS) on SV−2, and by Compact Total Electron Content Sensor and a micro dosimeter on both spacecraft	2013	[72]
FIREBIRD-1 FIREBIRD-2 FIREBIRD-3 FIREBIRD-4	1.5U	University of New Hampshire, Montana State University	Resolve the spatial scale and energy dependence of electron microbursts in the Van Allen radiation belts by using 1500 µm thick solid state silicon detectors	2013201320152015	[242,243]
ExoCube	3U	California Polytechnic State University	Measure global in-situ densities of [O], [H], [He], [N2], [O +], [H+], [He+], [NO+] in the upper ionosphere and lower exosphere by using an Ion Neutral Mass Spectrometer	2015	[172]
PropCube 1 PropCube 3	1U	Naval Postgraduate School	Ionospheric research performing dual frequency ionospheric calibration measurements of ionospheric electron density and irregularities	2015	[244]
CADRE	3U	University of Michigan	Measure the in-situ density, temperature and composition of the thermosphere plus neutral winds and ion flows by Wind Ion Neutral Composition Suite (WINCS)	2015	[174]
MinXSSMinXSS-2	3U	University of Colorado at Boulder	Study the energy distribution of solar soft X-ray emission and its impact on ionosphere, thermosphere and mesosphere by measuring solar spectral in 0.1–10 nm range by Amptek X123-SDD COTS X-ray Spectrometer	2015 In Devel.	[41,68]
Dellingr	6U	NASA Goddard Space Flight Center	Measure the composition and density of various ions and neutral elements in lower exosphere and upper ionosphere by an Ion Neutral Mass Spectrometer similar to ExoCube, and carry two magnetometers	In Devel.	[245]
ELFIN	3U	University of California, Los Angeles	Explore the mechanisms responsible for the loss of relativistic electrons from the radiation belts by a fluxgate magnetometer and two energetic particle detectors	In Devel.	[246]
SEAM	3U	Royal Institute of Technology	Conduct magnetic field measurement by using flux-gate magnetometer and other miniaturized magnetic sensor	In Devel.	[247]
OSIRIS-3U	3U	Pennsylvania State University	Investigate plasma transport in a stimulated ionosphere by using a Langmuir probe, a GPS occultation receiver, and a coherent electromagnetic radio tomography beacon	In Devel.	[248]
IGOSat	3U	Université Paris Diderot - Paris 7	GPS occultation receiver for measuring the total electronic content of the ionosphere and a scintillation detector for detecting high energy gamma-rays and electrons	In Devel.	[249]
SORTIE	6U	ASTRA	Determine the structure of equatorial plasma by using a miniature Ion Velocity Meter, and a micro Planar Langmuir Probe	In Devel.	[250]
DIME	1.5U	ASTRA	Space weather monitoring by two Langmuir probes, magnetometers, and four electric field probes on 3.5-meter cable booms	In Devel.	[251]
CINEMA 4	3U	University of California, Berkeley	Identical to CINEMA mission, 4 CubeSat constellation developed by University of California, Berkeley, Kyung Hee University of Seoul, and Imperial College London	In Devel.	[164]
CeREs	3U	NASA Goddard Space Flight Center	Study relativistic electron energizations and loss and loss due to microbursts as well as to study low energy solar flare electrons by Miniaturized Electron Proton Telescope	In Devel.	[252]
NEUTRON 1	3U	University of Hawaii at Manoa	Measure low energy neutron flux in the low Earth orbit by a neutron flux detector	In Devel.	[253]
ISX	3U	SRI International, California Polytechnic State University	Explore the three-dimensional structure of scintillation-scale ionospheric irregularities associated with Equatorial Spread F (ESF)	In Devel.	[254]
IT-SPINS	3U	Johns Hopkins University	Observe Ultra Violet nightglow radiance produced by the recombination of Oxygen ions with electrons in an upper ionosphere for producing a two-dimensional altitude/in-track tomographic images of the emissions	In Devel.	[255]
CuSP[a]	6U	Southwest Research Institute	Studying solar particles in interplanetary space and become a pathfinder for creating a network of “Space Weather Stations”	In Devel.	[152]
Astrophysics					
CXBNCXBN-2	2U	Morehead State University	Improve the precision of the measurements of the cosmic X-Ray background in the range of 30-50 keV by using a Cadmium Zinc Telluride (CZT) detector	2012 in Devel.	[176,177]
BRITE-A[TUGSAT-1]	7 kg GNB	Technical University of Graz (TUG)	BRITE-Constellation: Austria International nanosatellite constellation for monitoring photometrically, in two colors, the brightness and temperature variations of stars generally brighter than mag(V) ≈ 4	2013	[180]
BRITE-U [UniBRITE]	7 kg GNB	University of Vienna	BRITE-Constellation: Austria	2013	[180]
BRITE-P1 [Lem]	7 kg GNB	Polish Academy of Sciences	BRITE-Constellation: Poland	2013	[180]
BRITE-P2 [Heweliusz]	7 kg GNB	Polish Academy of Sciences	BRITE-Constellation: Poland	2014	[180]
BRITE-C1 [Toronto]	7 kg GNB	Canadian Space Agency, University of Toronto	BRITE-Constellation: Canada	2014	[180]

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Mission ID	Size	Organization	Objectives	Launch	Ref.
BRITE-C2 [Montréal]	7 kg GNB	Canadian Space Agency, University of Toronto	BRITE-Constellation: Canada Failure - did not separate properly from the upper stage of the rocket [181]	2014	[180]
S-CUBE	3U	Chiba Institute of Technology, Tohoku University	Global observation of meteors from LEO for estimating the meteoroid size, flux and compositions by using one camera to take visible images and 3 photomultiplier tubes to observe UV emissions from meteors	2015	[179]
ASTERIA	6U	NASA Jet Propulsion Laboratory	Look for transits of identified RV planets and conduct high cadence stellar photometry over long durations by a CMOS imager	In Devel.	[183]
HaloSat	6U	University of Iowa	Explore a hot galactic halo in the Milky Way Galaxy by mapping of the emission lines of oxygen in order to constrain its distribution and geometry by using three identical COTS Amptek X-ray detectors	In Devel.	[185]
PicSat	3U	LESIA, Observatoire de Paris	Detect the Beta Pictoris b transit predicted to happen between mid 2017 and mid 2018 by using a 50 mm telescope	In Devel.	[188]
Spaceborne In Situ Laboratory					
GeneSat−1	3U	NASA Ames Research Center	Biological experiment investigating the effects of microgravity on the metabolism of E. coli	2006	[190]
PharmaSat 1	3U	NASA Ames Research Center	Biological experiment studying the effects of microgravity on a laboratory yeast strain Saccharomyces cerevisiae and its resistance to antifungal agents	2009	[191]
O/OREOS	3U	NASA Ames Research Center	Biological experiment assessing the viability of microorganisms in the space environment and the stability of organic molecules in space	2010	[73]
Lambdasat	1U	Lambda Team	Studying the effects of radiation on graphene	2014	[193]
SporeSat−1	3U	NASA Ames Research Center	Biological experiment investigating the gravitational threshold for calcium ion channel activation in Ceratopteris richardii fern spores	2014	[92]
SporeSat−2	3U	NASA Ames Research Center	SporeSat−1 follow-up biological experiment mission scheduled to be launched in 2016	In Devel.	[192]
EcAMSat	6U	NASA Ames Research Center	Biological experiment investigating space microgravity effects on the dose-dependent antibiotic response and resistance of wildtype and mutant strains of uropathogenic E. coli	In Devel.	[93]
BioSentinel[a]	6U	NASA Ames Research Center	Biological experiment studying the damage and repair of DNA in an organism Saccharomyces cerevisiae in deep space	In Devel.	[94]
ChargerSat−2	1.5U	University of Alabama in Huntsville	Experiment investigating the heat transfer properties of nucleate boiling in microgravity	In Devel.	[198]
Q-PACE	2U	University of Central Florida	Experiment exploring fundamental properties of low-velocity particle collisions in microgravity for better understanding accretion in the protoplanetary disk	In Devel.	[195]
AOSAT	3U	Arizona State University	Space laboratory for studying planet formation and asteroid surface properties	In Devel.	[196]
Technology Demonstration					
NanoSail-D2	3U	NASA Marshall Space Flight Center, NASA Ames Research Center	Demonstrate the deployment of a large low mass solar sail and test its deorbiting capabilities. Re-flight of the NanoSail-D mission lost due to launch failure in 2008	2010	[58]
STARE ASTARE BSTARE C	3U	Lawrence Livermore National Laboratory	Demonstrate the feasibility of using nanosatellites for refining the orbital parameters of selected space objects by using an optical payload	20122013In Devel.	[256,257]
CANX-4CANX-5	6 kg GNB	University of Toronto	Dual-nanosatellite formation flying mission demonstrating a series of autonomous formations with sub-meter control and centimeter-level relative position knowledge	2014	[207]
TechEdSat-3 TechEdSat-4	3U	NASA Ames Research Center	Demonstrate Iridium satellite-to-satellite communications as well as an Exo-Brake passive de-orbiting system for accurate de-orbit and eventual re-entry control	20132014	[223,224]
GRIFEX	3U	University of Michigan, NASA Jet Propulsion Laboratory	On-Orbit validation of detector technology for the Panchromatic Fourier Transform Spectrometer (PanFTS) which is an imaging FTS designed for a Geostationary mission	2015	[202]
LightSail-ALightSail-B	3U	The Planetary Society	Two CubeSat mission designed to advance solar sailing technology state of the art	2015In Devel.	[57]
OCSD-AOCSD-BOCSD-C	1.5U	The Aerospace Corporation, NASA	3 AeroCube OCSD-A, -B, -C CubeSats to validate high-speed optical communications and small spacecraft proximity operations	2015In Devel.In Devel.	[203]
Nodes-ANodes-B	1.5U	NASA Ames Research Center	Demonstrate network capabilities critical to the operation of swarms of multiple spacecraft, based on the hardware and software developed for the lost EDSN eight 1.5U CubeSats mission	2015	[208]
VELOX-II	6U	Nanyang Technological University, Singapore	Demonstrate inter-satellite communication capability between a low earth orbit and a	2015	[209]

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Table A1 *(continued)*

Mission ID	Size	Organization	Objectives	Launch	Ref.
			geosynchronous orbit satellites for data relay		
ISARA	3U	NASA Jet Propulsion Laboratory	Demonstrate high gain Ka-band reflectarray antenna integrated into solar arrays for enabling downlink data rate of 100 Mbps	In Devel.	[76]
CPOD-ACPOD-B	3U	Tyvak Nano-Satellite Systems Inc.	Utilize several formation flying techniques to enable rendezvous, proximity operations, and docking with two identical 3U CubeSats	In Devel.	[210]
CANYVAL-X	1U 2U	Yonsei University, KARI George Washington University, NASA	Demonstrate distributed virtual telescope by enabling two nanosatellites to fly in a precise formation along an inertial line-of-sight	In Devel.	[213]
DelFFi-Delta DelFFi-Phi	3U	Delft University of Technology	Demonstrate autonomous formation flying between two identical Delta and Phi nanosatellites by using various Guidance, Navigation and Control (GNC) architectures	In Devel.	[211]
QARMAN	3U	von Karman Institute for Fluid Dynamics	Demonstrate reentry technologies, novel heatshield materials, passive aerodynamic drag and attitude stabilization systems, and the transmission of telemetry data during reentry via LEO satellite data relay	In Devel.	[225]
InflateSail	3U	Surrey Space Center, University of Surrey	Demonstrate a deployable sail with an area of 10 m^2, which sits atop a 1 m long inflatable rigidizable mast for a drag deorbiting	In Devel.	[258]
SAMSON-A SAMSON-B SAMSON-C	6U	Technion - Israel Institute of Technology	Demonstrate long-term autonomous cluster flight of three 6U satellites and determine the position of a cooperative terrestrial emitter based on time difference of arrival and/or frequency difference of arrival	In Devel.	[214]
RANGE-A RANGE-B	1.5U	Georgia Institute of Technology	Demonstrate two 1.5U CubeSats flying in a leader-follower formation with the goal of improving the relative and absolute positioning capabilities of nanosatellites	In Devel.	[212]
CanX−7	3U	University of Toronto	Demonstrate a lightweight, compact, deployable drag sail for a nanosatellite deorbit thus enabling customizable deorbiting device for nanosatellites and microsatellites in low Earth orbit	In Devel.	[226]
TEPCE-A TEPCE-B	1.5U	U.S. Naval Research Lab	Demonstrate electrodynamic tether propulsion in space by using two identical 1.5U CubeSats attached to each end of one kilometer electrically conducting tether	In Devel.	[204]
CryoCube	3U	Sierra Lobo, Inc., NASA Kennedy Space Center	Demonstrate deployable sunshield for achieving cryogenic temperatures in LEO	In Devel.	[96]
FalconSAT−7	3U	United States Air Force Academy	Demonstrate a deployable telescope with larger aperture than the spacecraft structure	In Devel.	[259]
AMODS	3U	United States Naval Academy	Demonstrate on-orbit inspections on conventional spacecraft by using one self-propelled transport CubeSat (BRICSat) to deliver one of several “repair” CubeSats (RSats) with manipulable arms to spacecraft for diagnostic and maintenance services designed to extend the life of that satellite	In Devel.	[215]
CubeRRT	6U	Ohio State University	Demonstrate and validate radio frequency interference (RFI) detection and mitigation technologies for future Earth observing microwave radiometers operating 6–40 GHz	In Devel.	[260]
RECONSO	6U	Georgia Institute of Technology	Demonstrate detection and tracking of resident space objects in the 1–10 cm size from a LEO CubeSat platform by using a visible light lens and a CMOS imager	In Devel.	[261]
GLADOS	6U	The State University of New York at Buffalo	Demonstrate space debris classification, as well as to characterize their size, shape, and material properties in geostationary orbit by using one visible and one near-IR cameras from LEO CubeSat platform	In Devel.	[262]
AeroCube−9 (LMPC)	3U	The Aerospace Corporation	Demonstrate a new linear mode photon counting (LMPC) detector as well as demonstrate CubeSat compatible cryocooler	In Devel.	[263]
SurfSat	2U	University of Central Florida	Investigate spacecraft charging issues due to the ambient, dynamic plasma environment	In Devel.	[264]
AAReST	3U 3U 15U	California Institute of Technology, University of Surrey–Surrey Space Center	Demonstrate an autonomous, in-orbit assembly of a space telescope using multiple mirror elements by launching two 3U “MirrorSats” and one central 15U “CoreSat”	In Devel.	[216]
MiTEE	3U	University of Michigan	Characterize voltage-current transfer functions for an electrodynamic tether (EDT) system under a variety of ionospheric plasma conditions by deploying a picosat size end-body from 3U CubeSat on 10 m EDT	In Devel.	[265]
iSat	12U	NASA	Demonstrate CubeSat maneuverability, including plane change, altitude change and change in its closest approach to Earth by using Hall thruster technology and iodine as a propellant	In Devel.	[266]
^{3}Cat−1	1U	Universitat Politècnica de Catalunya	Conduct multiple scientific experiments and demonstrate different technologies under hostile space conditions. The list of payloads includes a graphene transistor, a wireless power transfer system, MEMS, experimental solar panels, etc.	In Devel.	[194]

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