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CubeSat Technology Past and Present: Current State-of-the-Art Survey

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Executive Summary

A cube satellite (CubeSat) is an evolving and emerging technology that gives a novice or advanced researcher relatively affordable access to space research experiments and applications. The initial CubeSat standard was created in 1999 by California Polytechnic State University, San Luis Obispo and Stanford University's Space Systems Development Lab to facilitate direct access to space for university students. This initial CubeSat standard has now been adopted by hundreds of organizations worldwide and includes not only universities, educational institutions, but private firms and government organizations. Dozens of CubeSats have been launched since 2003 and have come from more than 29 states in the United States. The CubeSat standard facilitates frequent and affordable access to space with launch opportunities available on most launch vehicles.

CubeSats are a class of research spacecraft called nanosatellites and are built to standard CubeSat Units or U dimensions of 10 by 10 by 10 cm and are formally classified as 1U, 2U, 3U, or 6U in size. Most CubeSats are deployed from a Poly-Picosatellite Orbital Deployer called a P-POD. Partnerships among NASA, U.S. industry, and educational institutions are being formed to build upon existing successful CubeSat initiatives with a goal to expand and include launching 50 small satellites from 50 states within the next several years.

An extensive and detailed literature review that includes over 830 citations has been conducted to provide a comprehensive resource on both NASA and non-NASA CubeSat experiments and applications that can serve as a guide for background information on CubeSats as well as a valuable resource of lessons learned from CubeSats that have been launched in the past.

CubeSats are currently being launched from all over the world on different launch vehicle platforms. Some organizations providing launch opportunities are California Polytechnic State University (http://www.cubesat.org/contactus), ISISPACE Group (https://www.isispace.nl/), Nanoracks (http://nanoracks.com/), Spaceflight Industries, Inc. (http://spaceflight.com/), TriSept Corporation (https://trisept.com/), and Tyvak Nano-Satellite Systems, Inc. (https://www.tyvak.com/).

CubeSat Background and History

A cube satellite (CubeSat) is a nanosatellite and is any satellite that has a total mass of between 1 to 10 kg. In general, the term "nanosatellite" also covers all CubeSats, PocketQubes, TubeSats, SunCubes, ThinSats, and nonstandard picosatellites.

The original CubeSat Project concept in 1999 was a collaborative research effort between Dr. Jordi Puig-Suari at California Polytechnic State University (Cal Poly), San Luis Obispo, and Professor Bob Twiggs at Stanford University. Their goal was to develop a new class of picosatellites, also referred to as the "CubeSat standard" (Ref. 1). The CubeSat standard is defined in the CubeSat Design Specification (CDS), rev. 13 (Ref. 2). The CDS is an initial resource that covers the general, mechanical, electrical, operational, as well as testing requirements in order to launch a CubeSat. However, one cannot launch just a solitary CubeSat but must also consider the deployment system. Typically, if a CubeSat is launched in the United States, a Poly-Picosatellite Orbital Deployer (P-POD) is the CubeSat deployment system. Figure 1 shows what a standard P-POD and cross section should look like.

A typical P-POD is capable of carrying three standard CubeSats and serves as the interface between the CubeSat and the launch vehicle. The P-POD is essentially a rectangular box with a door and a spring mechanism that is utilized to deploy the CubeSat. Once the release mechanism of the P-POD is actuated by a deployment signal from the launch vehicle, a set of torsion springs at the door hinge force the door open and the CubeSats are deployed by the main spring gliding on its rails and the P-POD rails. The P-POD is made up of anodized aluminum. CubeSats must be compatible with the P-POD to ensure the safety and success of any mission. The P-POD is also backwards compatible since any CubeSat within the CDS rev. 9 or later will not have compatibility issues. Any person seeking to deploy a CubeSat should design to the most recent CDS to take full advantage of the P-PODs features (Ref. 2). The P-POD plays a vital role as it serves as the unique interface between the launch vehicle and the CubeSat.

There are 11 general requirements in order to conform to a typical CubeSat specification. In addition, there are 17 CubeSat

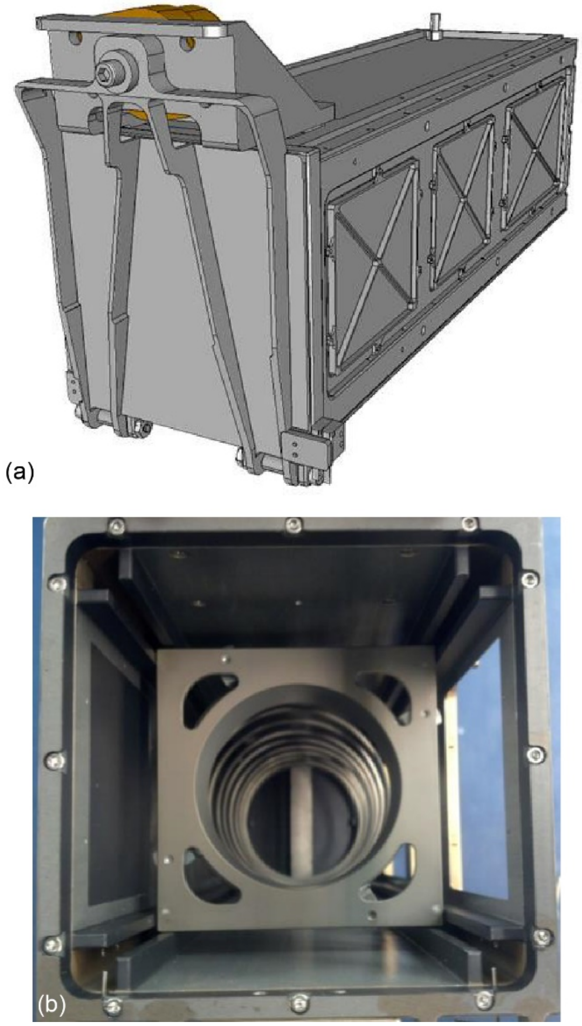

Figure 1.—Poly-Picosatellite Orbital Deployer (P-POD). (a) P-POD. (b) Cross section (from Ref. 2).

mechanical requirements, nine electrical requirements, seven operational requirements, and five testing requirements that need to be met in order to gain approval to deploy a CubeSat. All requirements are listed in CDS rev. 13 (Ref. 2).

There are currently six different approved sizes for CubeSats in the United States including 1U, 1.5U, 2U, 3U, and 6U, and all have unique requirements. A 1U CubeSat is limited to a 100- by 100- by 113.50-mm volume and must typically weigh less than 1,000 g. A 1.5U CubeSat is limited to a 100- by 100- by 170.2-mm volume and must typically weigh less than 1,500 g. A 2U CubeSat is limited to a 100- by 100- by 227.0-mm volume and limited to 2,000 g. A 3U CubeSat is limited to a 100- by 100- by 340.5-mm volume and limited to 3,000 g. A 6U CubeSat is limited to a 100- by 226.3- by 386.0-mm volume and limited to 6,000 g. Each CubeSat has a minimum requirement for springs and deployment switches that must be adhered to (Refs. 2 and 3).

In the United States, there have been dozens of documented CubeSat missions dating back to 2003 with the Eurokot Launch. Table I contains a sampling of launch dates and CubeSats launched. A complete list of the actual CubeSat launches can be searched on the official CubeSat website (Ref. 4).

According to an international nanosatellites database (Ref. 4), there have been 1,186 nanosatellites launched of which 1,088 have been CubeSats. There have been two interplanetary CubeSat launches, 87 nanosatellites have been destroyed on launch, there are 64 countries with nanosatellites and there are over 3,000 nanosatellites predicted to be launched worldwide in the next 6 yr (Ref. 5).

One of the most valuable resources for CubeSats is the CubeSat developer's conference. A complete list of all CubeSat workshops dating back to 2004 can be found in one location (Ref. 6). This is one of the most comprehensive presentation databases on CubeSats for anyone interested in launching a CubeSat.

In presenting the background and history of CubeSats, one may find the most overlooked barrier to the novice person interested in launching a CubeSat is price or just how much it costs to launch a CubeSat. It is estimated that a CubeSat launch can cost as little as $10,000 to as much as $500,000 depending on what type of CubeSat you are interested in launching. There are companies that will sell you a CubeSat kit that you can utilize to build your own CubeSat, but you will still need a way to launch it into space. There are several organizations that offer an experimenter the ability to propose a CubeSat experiment and they will provide all of the funding needed. One such organization is NASA and their CubeSat Launch Initiative (CSLI) (Ref. 7).

NASA CSLI provides access to space for small satellites, CubeSats, developed by the NASA centers and programs, educational institutions, and nonprofit organizations giving CubeSat developers access to a low-cost pathway to conduct research in the areas of science, exploration, technology development, education, or operations.

Through the Educational Launch of Nanosatellites (ELaNa) missions, International Space Station (ISS) deployment opportunities, or rideshare launches to space via existing launch services of government, payloads are provided, as well as dedicated CubeSat launches from the newly selected contracts for the CubeSats selected through CSLI. To participate in the CSLI program, CubeSat investigations should be in alignment with the NASA Strategic Plan.

TABLE I.—CUBESAT MISSIONS

Launch date	CubeSat launched
6/20/2003	Eurokot
10/27/2005	Kosmos 3M Student Space Exploration and Technology Initiative (SSETI) Express Launch
2/22/2006	M–V–8 ASTRO–F
7/26/2006	Dnepr EgyptSat
12/16/2006	Minotaur I TacSat–2
4/17/2007	Dnepr launch completed
5/19/2009	Minotaur I TacSat–3
9/23/2009	PSLV–C14
11/20/2010	Minotaur IV STP–S26
12/8/2010	Falcon 9 Dragon
4/4/2011	Taurus XL Glory
10/28/2011	Delta II NPP
2/13/2012	Vega Maiden
9/13/2012	Atlas V OUTSat (Operationally Unique Technologies Satellite)
4/18/2014	Falcon 9 CRS–3 (Commercial Resupply Services—3)
6/19/2014	Dnepr UniSat–6
1/31/2015	Delta II SMAP (Soil Moisture Active Passive)
5/20/2015	Atlas V ULTRASat (Ultra Lightweight Technology and Research Auxiliary Satellite)
10/8/2015	Atlas V GRACE (Government Rideshare Advanced Concepts Experiment)
11/5/2015	ElaNa–7 (Educational Launch of Nanosatellites—7) Super Strypi
11/13/2017	Delta II JPSS–1 (Joint Polar Satellite System—1)/ ELaNa–14
9/18/2018	Delta II ICESat–e (Ice, Cloud and land Elevation Satellite)/ELaNa–18

The CSLI is an integrated cross agency collaborative effort led by NASA Human Exploration and Operations Mission Directorate to streamline and prioritize rideshare and deployment opportunities of CubeSats. CSLI opportunities are available to NASA centers, U.S. not-for-profit organizations, and accredited U.S. educational organizations. In the past, selected science investigation missions have studied Earth's atmosphere, near-Earth objects, space weather, and biological sciences. Technology demonstration missions have included in-space propulsion, space power, radiation testing, and solar sails.

By providing a progression of educational opportunities including CSLI for students, teachers, and faculty, NASA assists the Nation in attracting and retaining students in the science, technology, engineering, and mathematics (STEM) disciplines. This strengthens the future workforce of NASA and the Nation. Further, the CSLI promotes and develops innovative technology partnerships among NASA, U.S. industry, and other sectors for the benefit of Agency programs and projects. NASA thus gains a mechanism to use CubeSats for low-cost technology development or pathfinders.

Since its inception, 85 CubeSat missions have been flown on 22 ELaNa Missions with 34 manifested for flight. ELaNa missions have included: BisonSat (first CubeSat built by a tribal college), TJ3Sat (first CubeSat built by a high school), and the St. Thomas More Satellite 1 or STMSat–1 (first CubeSat built by an elementary school).

NASA has selected and prioritized 176 CubeSat missions from 93 unique organizations representing 39 states and the District of Columbia. The 39 states include the following: Alabama, Alaska, Arizona, Arkansas, California, Colorado, Connecticut, Florida, Georgia, Hawaii, Idaho, Illinois, Indiana, Iowa, Kansas, Kentucky, Louisiana, Maryland, Massachusetts, Michigan, Minnesota, Missouri, Montana, New Jersey, New Mexico, New York, North Dakota, Ohio, Oregon, Pennsylvania, Rhode Island, Tennessee, Texas, Utah, Vermont, Virginia, Washington, West Virginia, and Wisconsin (Ref. 7). References 8 and 9 list past NASA CubeSat launches dating back to 2011 as well as upcoming CubeSat missions.

If one does not have access to NASA resources or is unsuccessful in obtaining a proposal for a CubeSat launch, then private funding can still be an option. There are several companies that provide CubeSat services, from initial concept to launch with variable pricing based on CubeSat configuration.

It should be noted that the CubeSat standard has been highly successful. Since 2014, more than half of the satellites that were launched into orbit were CubeSats (Ref. 10) and today, there are more commercial CubeSat launches than academia due to the fact that when compared to conventional satellites, CubeSats are inexpensive to develop and launch and can be networked together to form constellations.

CubeSats are primarily utilized by academia for research, government entities and the military for science purposes, and commercial companies for applications such as telecommunications, video, and sensing applications. However, many CubeSat missions fail to launch. It is estimated that since 2000, over 40 percent of CubeSat missions were categorized as launch fail, dead on arrival, or early loss (Ref. 10). As many CubeSat missions are transitioning away from academic towards commercial venture, reliability expectations are changing, and mission lifetimes are being extended from months to years with reliability being paramount for these durations.

What follows is more specific CubeSat missions, launches, experiments, and technologies that have had a significant impact in the CubeSat community and can be used as a guide or lessons learned for anyone interested in launching a CubeSat in the future. We specifically concentrated on four major areas: (1) thermal management, a process that needs to be performed to ensure proper outgassing of all CubeSat components, (2) deployment mechanisms, which must be designed to meet the P-POD Cal Poly standard, (3) power generation, which is limited to 10 W and the available onboard power, and (4) communications, where CubeSat operators need to comply with their country's radio license agreements and restrictions. In addition, we have included an extensive bibliography to serve as a reference list for hundreds of CubeSat research technologies, projects, experiments, and launches that are applicable to the field of CubeSat research and development.

CubeSats and Thermal Management

As part of the CubeSat testing and validation process, CubeSats need to pass a thermal vacuum bakeout process, which needs to be performed to ensure proper outgassing of all CubeSat components. The test specification for thermal vacuum bakeout is typically outlined by the launch provider (Ref. 1).

In a vacuum environment, heat is transferred in by way of radiation and conduction. The internal environment of a fully enclosed small satellite is usually dominated by conductive heat transfer, while the overall energy balance and outside environment are driven purely via thermal radiation. The thermal radiation environment is manipulated by using materials that have certain specific radiative properties, commonly referred to as "solar absorptivity" (implying wavelengths in the range of approximately 0.3 to 3 μm) and infrared (IR) emissivity (approximately 3 to 50 μm). Solar absorptivity governs how much of the impinging solar flux a spacecraft absorbs, while IR emissivity determines how well a spacecraft emits its thermal energy to space, relative to a perfect blackbody emitter. These properties are almost entirely surface properties of a material and can be modified simply by adding specialized coatings, platings, polishings, or even adhesive tapes of specific materials (Ref. 11).

Thermal insulation acts as a thermal radiation barrier from incoming solar flux and also to prevent excessive heat dissipation. Components used to ensure the temperature requirements are met in CubeSats include multilayer insulation (MLI) as well as heaters for the battery. MLI blankets are typically used as thermal insulation to maintain a temperature range for the electronics and batteries during orbit, or more recently, for biological payloads. In addition, metalized tapes are becoming increasingly common for small spacecraft applications. MLI is fairly delicate and drops drastically in performance if compressed, so it should be used with caution or avoided altogether on the exterior of small satellites that fit into a deployer such as a P-POD. Another passive method of thermal control is the application of matte paint, which can alter the solar absorbance and IR emittance of a surface material (Ref. 11).

It is important to conduct experimental analysis and simulation of any spacecraft's thermal output in order to optimize a CubeSat's thermal management components and techniques. CubeSats with special thermal concerns, often associated with certain deployment mechanisms and payloads may have to be tested in a thermal vacuum chamber before a successful launch.

Satellites in orbit are heated by radiative heat emitted from the Sun directly and reflected off Earth. Heat is also generated by the CubeSat's components and must be cooled by radiating heat into space if the environment is cooler than the spacecraft. All radiative heat sources and sinks are rather constant and very predictable as long as the CubeSat's orbit and eclipse time are known (Ref. 11).

What follows is a review (Refs. 11 to 27) of CubeSat thermal management research conducted in the recent past.

Anderson et al. (Ref. 12) investigated the need for advanced cooled electro-optical instrumentation in remote observations of the atmosphere as demonstrated by Sounding of the Atmosphere Using Broadband Emission Radiometry (SABER) on the Thermosphere Ionosphere Mesosphere Energetics Dynamics (TIMED) mission. The relatively new use of small satellites in remote Earth-observing missions, as well as the challenges, are epitomized by the upcoming National Oceanic and Atmospheric Administration (NOAA) Earth Observing Nanosatellite—Infrared (EON–IR) 12U CubeSat missions. These advanced CubeSat missions, which hope to accomplish scientific objectives on the same scale as larger more traditional satellites, require advanced miniaturized cryocoolers and active methods for thermal management and power control. The

Active CryoCubeSat (ACCS) project is a demonstration of such a technology. Utilizing ultrasonic additive manufacturing (UAM) techniques, a mechanically pumped fluid loop (MPFL) and miniature pumps and cryocoolers are used to create a closed-loop fluid-based heat interchange system. The ACCS project creates a two-stage thermal control system (TCS) targeting 6U CubeSat platforms. The first stage is composed of a miniature Ricor K508N cryocooler, while the second is formed by a UAM-fabricated heat exchanger MPFL system powered by a TCS Micropumps Limited, M510 micropump. The working fluid is exchanged between a built-in chassis heat exchanger and a deployable tracking radiator. This work details the theory design and testing of a relevant ground-based prototype and the analysis and modeling of the results as well as the development of a design tool to help in customized active thermal control designs for small satellites. Ultimately, the ACCS project hopes to enable a new generation of advanced CubeSat atmospheric observing missions.

Athirah et al. (Ref. 13) discuss the stress and thermal analysis on the CubeSat structure to study the survivability of the CubeSat during the launching process or operating condition at the orbit. Various designs of mechanical structures were analyzed to determine the best design for different mission requirements. Analysis on the temperature of the batteries was conducted as it is one of the most critical components that must operate in the required temperature to avoid failure of the CubeSat. ANSYS 13.0 (Ansys, Inc.) was used to simulate both the structural and thermal analysis. Static structural analysis was used to study the impact of g-force on the CubeSat during the launching process, and Icepak (Ansys, Inc.) was used to study the internal temperature. The results were compiled in table form and comparisons were made among different designs to determine the advantages and disadvantages of each design. Results from simulation such as safety factor, weight, internal available space, and battery discharge rate were analyzed. They surmised that there is no best design in the CubeSat structure but only the most suitable design for the mission purposes and battery discharge rate will play an important role to determine the requirement of a heater in the CubeSat.

Thanarasi (Ref. 14) investigates the thermal analysis of CubeSat in a hot and cold worst-case environment using finite element analysis. Since the thermal subsystem is not independent of other devices, it is important to know how all elements in the spacecraft can have an influence on the thermal environment, either by emitting or absorbing energy or both. Their finite element analysis methodology was used in order to determine the spacecraft's operating temperature ranges. They used MSC Nastran and MSC Patran software (MSC Software Corporation) as their finite element analysis modeling tool. The design of their thermal system was based on passive methods and this approach is vital to avoid power consumption in cases where it would not be necessary. The goal is to design a thermal subsystem to operate the spacecraft throughout its mission phases without any failure.

Butler-Craig (Ref. 15) investigates the thermal behavior of high power density 3U CubeSats that are capable of supporting high-impulse missions. This mission is a technology demonstration of a 100-W power management and distribution system aboard a small-volume CubeSat that can serve as evidence of CubeSats being able to provide high power to the subsystems necessary to support high-impulse missions. They explored the thermal behavior of a CubeSat subjected to substantial waste heat due to extra power generation. They also conducted a thermal vacuum test and concluded that, despite 100 W of waste heat being deposited into the system, the thermal limits of the electrical components were not exceeded and remained at steady-state operable temperatures. The thermal vacuum test proved that the Advanced Electrical Bus (ALBus) CubeSat was able to provide enough power without overheating to the detriment of its electrical components. The study is intended to enhance the feasibility assessment of high power density CubeSats capable of high-impulse missions.

Gorev et al. (Ref. 16) discuss the thermal deformation of a 3U CubeSat in low Earth orbit (LEO) and the impact of uneven heating. Their calculations showed that the thermal deformation of a CubeSat structure in orbit caused a deviation between normals to opposite small satellite sides of about 0.03°. This deviation is commensurate with the required satellite pointing accuracy, approximately 0.1°, necessary for satellite laser communication. Their study shows that to solve similar problems in the CubeSat designing that require this or better CubeSat pointing accuracy, it is necessary to consider the expected satellite structure thermal deformation.

Ibrahim and Yamaguchi (Ref. 17) conducted a study aimed at predicting the types of thermally induced dynamics that can occur on CubeSats that fly in LEO. They utilized four short-edge deployable solar panels based on historic temperature profiles using thermal analysis software. The results were used in a numerical simulation to determine the structural response of the solar panels and the effect of pointing the direction of the satellite using inertia relief methods. They concluded that the thermal snap motion could occur during eclipse transition due to rapid temperature changes in the solar panel's cross sections. Their work examines how temperature affects the solar panels pointed toward the Sun throughout the daylight period and pointed to the Earth while in the shadow to calculate and predict the potential temperature profile differences that can affect CubeSats.

Nader (Ref. 18) researches the use of carbon nanotubes for thermal distribution and transfer bus systems for 1U CubeSats. He and his team reviewed the need to develop a heat dissipation and transfer system for components on the NEE–01 Pegasus satellite in order to avoid freeing while the satellite was in the eclipse part of its orbit. Several materials and designs were tested in order to achieve the best thermal transfer rates as indicated by the specifications. Extensive testing from the manufacturing specifications of target components was conducted until they achieved the best results using multiwalled carbon nanotube sheets to manufacture a thermal transfer bus. This thermal transfer system will allow the spacecraft to route the internally generated heat, as well as any heat coming from outside their MLI to penetrate the external hull, to be efficiently sinked to their four battery arrays that are used as thermal dissipation masses. In order to ensure the survival of commercial-off-the-shelf (COTS) electronics longer than any other previous missions, they designed a miniature version of an MLI system. The requirements were to fend off up to 60 percent of incoming heat, to protect the electronics against alpha and beta particles, to shield them from plasma discharges, and to attenuate most of X and gamma radiations. The result was the SEAM/NEMEA Space Environment Attenuation Manifold, a multistage MLI capable of blocking alpha, beta, X, and gamma radiations and to block up to 67 percent of incoming heat, while retaining internal heat over the eclipse phase, NEMEA can also attenuate and even neutralize electromagnetic pulse and plasma discharge events.

Garzón and Villanueva (Ref. 19) presented a model for predicting the temperature of 3U CubeSat in a LEO, which supposes a single temperature common to all satellite components. The report includes a detailed analytical computation of the external heat fluxes for a particular orbit and spacecraft assumptions based on the features foreseen for satellite Libertad 2 under development at Universidad Sergio Arboleda. He and his team computed the heat fluxes and their associated temperature for all possible orbital orientations and combined these results with a description of the satellite orbital plane rotation (nodal regression) and the solar motion on the ecliptic. The goal is to determine the minima and maxima of the orbital temperature oscillation for a mission lifetime of a year. They found that for feasible model parameters, the temperature extremes are mostly within the operating temperature range of the most sensitive satellite component, $0 \leq T \leq 60$ °C, which suggest mission viability. The report also discusses possible model improvements that would allow testing of satellite design upgrades. It surmises that the calculation of the external heat fluxes described can be carried over, relatively unchanged, to a more accurate model describing heat transfer between satellite parts with different temperatures.

Darbali-Zamora, Cobo-Yepes, and Ortiz-Rivera (Ref. 20) present the effects that varying temperature conditions have on the efficiency of size constrained electronic power supply (EPS) subsystems designed for the power management of small satellites. In general, the power distribution of a CubeSat is composed of multiple direct current to direct current converters that provide maximum power point tracking (MPPT) and voltage regulation. The performance of these converters can be affected when operating at extreme temperature conditions. Typically, a CubeSat EPS can be subjected to temperatures of –40 up to 80 °C. For this reason, thermal considerations during the design process of the EPS are vital. This article illustrates an EPS prototype designed, constructed, and tested to withstand low- and high-temperature conditions found in space. Efficiency results are also obtained under different thermal conditions.

Thaheer (Ref. 21) measured electron density for the Malaysia Youth Satellite (MYSat) CubeSat with the primary objective of measuring the electron density in ionosphere E layer for validation of the electromagnetic model for natural disaster management developed by Universiti Sains Malaysia while at the same time developing university capabilities in building nanosatellites. This project was designed to inspire and prepare future space professionals by providing university students with practical experience in all parts of a real space project and to improve their motivation to work in the fields of space technology and science, this way helping to ensure the availability of a suitable and talented workforce in the future. In collaboration with the Malaysian Space Agency, university students produced an orbit simulation using Analytical Graphic, Inc.'s System Tool Kit (STK) software and the results of the mission design include orbital lifetime, ground track accessibility, and lighting times. Using those results, preliminary design of each subsystem, such as thermal, structure, power, communication, and attitude control, can be constructed.

Rievers, Milke, and Salden (Ref. 22) designed a CubeSat in situ degradation detector for the TCS. In order to evaluate this system, material parameters specifying the conductive and radiative properties of the different TCS components have to be known including their respective variations within the mission lifetime. More specifically, the thermo-optical properties of the outer surfaces including critical TCS components such as radiators and thermal insulation are subject to degradation caused by interaction with the space environment. The evaluation of these material parameters by means of ground testing is a time-consuming and expensive endeavor. Long-term in situ measurements on board the ISS or large satellites not only realize a better implementation of the influence of the space environment but also imply high costs. Motivated by this fact, a nanosatellite-scale degradation sensor concept that realizes low power consumption and data rates compatible with nanosatellite boundaries at ultra-high frequency (UHF) radio was developed. By means of a predefined measurement and messaging cycle, temperature curves were measured and evaluated on ground to extract the change of absorptivity and emissivity over mission lifetime.

Isaacs et al. (Ref. 23) developed FlexCool technology that optimizes flat heat pipes for optimal thermal management of CubeSats. For this application, they performed initial testing and modeling of a flat, conformable, lightweight, and efficient two-phase heat strap called FlexCool, currently being developed at Roccor1. Using acetone as the working fluid, the heat strap has an average effective thermal conductivity of 2,149 W/m·K, which is approximately four times greater than the thermal conductivity of pure copper. In addition, the heat strap has a total thickness of only 0.86 mm and is able to withstand internal vapor pressures as high as 930 kPa, demonstrating the suitability of the heat strap for orbital environments where pressure differences can be large. A reduced-order, closed-form theoretical model was developed in order to predict the maximum heat load achieved by the heat strap for different design and operating parameters. The model is validated using experimental measurements and is used here in combination with a generic algorithm to optimize the design of the heat strap with respect to maximizing heat transport capability.

Yamaoka et al. (Ref. 24) explain that while it is known that cosmic rays are accelerated and propagated to the Earth in association with solar flares, the particle acceleration mechanism is still unknown. Only neutrons can be a direct probe to clarify the ion acceleration mechanism in the Sun because they are not affected by the magnetic field, and thus directly travel to the Earth with original acceleration information. There have only been a few 10-s solar neutron events detected since their discovery in 1980 because the energy is attenuated by the Earth's atmosphere and previous ground-based neutron detectors have insufficient sensitivity. One space-based detector on board the ISS and dedicated for solar neutron observation has detected more than 20 solar neutrons so far but suffers from secondary neutron background from the huge mass of the ISS itself. Small satellites with a tiny mass are expected to perform highly sensitive observation with much smaller neutron background. They discuss a CubeSat designed to detect neutrons whose energies are lower than 100 MeV. The satellite should consist of a very compact and high-sensitive solar neutron spectrometer and supporting bus system. The detector utilizes novel photon-detector MPPC (Multi-Pixel Photon Counter), which realizes the smaller detector size. This device has not been used in the space environment and its on-orbit verification is another purpose of this mission. For the satellite system design, this mission requires a relatively large power budget because continuous observation during sunshine should be realized as much as possible. In addition, the detector should be kept at low temperature to reduce the thermal noise of the MPPC. The planned CubeSat design is to equip the custom-made radiator, which is made from the novel composite material that has a high thermal conductivity, and a novel power management system with the model-based battery status estimator. They describe the details of this satellite system design status to achieve the mission requirements.

Al Qasim et al. (Ref. 25) developed the Nayif–1 CubeSat, which was the first CubeSat mission from the United Arab Emirates (UAE). The Nayif–1 mission goal was to make space technologies more accessible to universities in the UAE. Nayif–1 is a 1U Amateur Radio communications satellite that was on board a Falcon 9 rocket in 2016. The four main goals of the mission were to characterize, validate, and study the accuracy of its thermal model with in situ temperature measurements in space; determine and study the evolution of the solar cells performance in space during the mission design life of 1 year; allow high-school-level students to determine Nayif–1's orbital velocity using the Doppler shift effect observed through the ground station; and allow secondary and tertiary students to emit short text messages using the Nayif–1 satellite.

Janzer et al. (Ref. 26) investigated TCSs for high-power applications on CubeSats based on the increase in CubeSat missions with energy demanding payloads and the ongoing miniaturization of electric components. For upcoming commercial and scientific missions, it is important to overcome thermal challenges and provide the necessary thermal conditions for demanding payloads and subsystems in the dense packaging of the CubeSat form factor. CubeSats evolved from mostly educational tools to accepted platforms for business and science and thus thermal management for small spacecraft gained more and more significance over the last few years. In past research, the Technical University of Munich focused on thermal modeling of CubeSats and passive thermal control mechanisms. They have continued this research effort for high-power applications for CubeSats where passive thermal control might not be sufficient. The inherent limits of the CubeSat form factor strongly limit the option for active thermal control. In order to evaluate the active thermal control mechanisms, they have summarized mathematical models of the physical principles and give an overview of preliminary calculations. A case study with a power-demanding electric propulsion system for CubeSats showed the feasibility of the evaluated mechanisms. They present the results of using various TCSs in a reference mission in ESATAN–TMS (ITP Aero), giving a first evaluation of the impact each thermal control method has on the designed mission and the electric propulsion system.

Lastly, a LARES (Laser Relativity Satellite) system, which was the first payload of the new Vega European launcher successfully launched from Kourou spaceport on February 13, 2012. The LARES system's primary goal was to deploy the LARES. The LARES's main goal is the measurement with high accuracy of the Lense-Thirring effect. Two secondary objectives were assigned to the mission: to provide a separation platform for additional payloads and to support the launcher qualification. The LARES system successfully deployed Alma Mater Satellite—1 (ALMASat–1), an Italian microsatellite, and seven European Space Agency (ESA) picosatellite CubeSats, educational payloads. In order to support Vega qualification, the system included standalone telemetry avionics devoted to monitor the payload bay environmental conditions during the different flight phases and providing video recording of lift-off and launcher stages separation, and of payload ejections, by two cameras. They describe the TCS of the LARES system, and the last-minute recovery actions carried on the hardware, to cope with the updated environmental conditions, communicated a few months before the launch when the hardware was already stored and ready for integration on the launcher. In addition, the LARES thermal description is provided and a set of thermal models were built (Ref. 27).

CubeSats and Deployment Mechanisms

As part of the standardized CubeSat deployment system, a CubeSat design must meet the P-POD Cal Poly standard. As mentioned in the introduction, the P-POD is a rectangular box with a door and a spring mechanism. Once the release mechanism of the P-POD is actuated by a deployment signal sent from the launch vehicle, a set of torsion springs at the door hinge force the door open and the CubeSats are deployed by the main spring gliding on its rails and the P-POD's rails. CubeSats slide along a series of rails during ejection into orbit. CubeSats must be compatible with the P-POD to ensure the safety and success of the mission by meeting the requirements (Refs. 1 to 3).

The CubeSat deployment mechanism challenge becomes how to design a reliable and innovative deployment mechanism solution that can be implemented now and for future missions successfully. Most CubeSat deployment systems utilize some sort of mechanical spring to provide the ejection force upon deployment. Mechanisms such as tape springs are often used on satellites to deploy solar panels, antennas, telescopes, and solar sails. Their main advantage comes from the fact that their motion results from the elastic deformation of structural components. CubeSats have problems in designing antenna deployment systems due to the challenge of packaging the whole deployable structure in a small spacecraft.

CubeSats have the potential to provide the means to explore space and to perform science in a more affordable way. In order to facilitate reliable data collection from sensitive instruments, deployable booms provide a means of separation from the spacecraft. Inflatable structures and antennas can be packaged efficiently occupying a small amount of space, and they can provide, once deployed, large dish dimension and correspondent gain. The more relaxed control requirements typically relevant to CubeSat missions open the door for innovative technologies that can replace large and expensive legacy attitude control and propulsion systems.

One significant issue with the number of CubeSat missions that have occurred is the issue of orbital debris handling and mitigation. Since the beginning of the space era, a huge amount of debris has progressively been generated. Most of the objects launched into space are still orbiting the Earth and today these objects represent a threat both in space and on Earth. The presence of space debris incurs risk of collision and damage to operational satellites. A credible solution has emerged over recent years, namely, actively removing heavy debris objects by capturing them and then disposing of them by destructive reentry in the Earth's atmosphere. This includes reducing the amount of debris, minimizing the risk of in-space collisions, and minimizing the hazards to persons and property on the ground from debris reentry. The safety and feasibility of future space missions strictly depends on the development of studies concentrating on active debris removal solutions.

As the need for high-gain antennas for CubeSats begin to evolve, deployable reflector antennas have regained significant interest. A particular class of deployable reflectors known as umbrella reflectors have been considered for several CubeSat missions. Large deployable antennas (LDAs) are an upcoming technique used as spaceborne reflector antennas. Low stow volume and mass are the key advantages allowing big reflector diameters to be launched on conventional vehicles. A primary concern in reflector antenna building is surface accuracy, especially at high operating frequencies. Conventional LDAs use sophisticated high-cost mechanics to deploy a mesh structure with low surface error. Deployable structures are also used as a drag sail to deorbit satellites when their lifetime is exceeded.

What follows is an extensive review (Refs. 28 to 109) of CubeSat deployment mechanics research ranging from LDAs, inflatable antennas, tethered CubeSat deployment, and more importantly, CubeSat missions dedicated to debris mitigation and the safety of CubeSat launches now and in the future.

Abdelwahab, Nawari, and Abdalla (Ref. 28) discuss a Sun-tracking solar cell array system concept to develop a maximum power point tracker for the UOKSat–3 CubeSat, a 2U CubeSat with deployable solar panels. This report details the effectiveness and importance of the tracking process, the impacts of the tracking mechanism on the attitude determination and control, and their interfacings to rotate the CubeSat. It also presents the MPPT's performance and its results to study the change of the input energy.

Rawashdeh et al. (Ref. 29) describe the design, modeling, and analysis of an attitude control system for a ram-facing picoclass satellite in LEO. A 3U (30 by 10 by 10 cm^3) CubeSat is designed to maintain one 10 by 10-cm^2 face aligned with the velocity vector throughout the orbit. The solution presented implements deployable drag fins and resembles a shuttlecock design, which is shown to be capable of providing passive stabilization for orbits below 500 km. A simplified Direct Simulation Monte Carlo (DSMC) method is used to model the rarefied atmosphere and its interaction with the spacecraft body for a range of fin geometries. Stability characteristics and pointing errors are shown for altitudes ranging from 300 to 450 km with fin lengths from 2 to 30 cm at angles from 0° to 90°.

Atas, Demiral, and Tekinalp (Ref. 30) analyze boom deployment vibration for a solar sail 3U CubeSat. The damping of the boom vibration using shape memory alloys is examined. They found that shape memory alloys do not reduce vibration below a certain level. Vibration damping via inherent friction in the deployment system is also considered. The analysis showed that the vibration may be completely damped due to the inherent friction in the deployment system.

Vilán et al. (Ref. 31) reported the results for the antenna deployment mechanism on the CubeSat (Refs. 1 and 4) Xatcobeo picosatellite that was launched in 2012. The main feature of the device is its extremely lightweight, achieved by using polymeric materials and additive manufacturing. Analysis was not only made of detailed characteristics but also of the advantages of using this combination, its validity after almost 2 years of perfect operation in orbit on Xatcobeo, and its latest operational success on HumSat–D. The results show that it deployed as expected in orbit and that it continues to operate correctly on both missions, not only in terms of the deployment mechanism but also the materials used. The analysis focuses on the mechanism's operational reliability and long useful lifetime.

Martinotti (Ref. 32) presented a mechanical design of a deployable solar panel system for Sun-pointing 1U, 2U, and 3U CubeSats. The basic idea is to enlarge the solar panels total surface with 12 multiple-deployable panels. The deployable system uses four solar panels connected to the Sun-pointing face (+Z) of the satellite and four couples of panels connected to the opposite one (–Z). Solar panels unfold simultaneously using torsion springs designed according to the size of the CubeSat. After opening, the four panels of +Z face rotate 45° around the vertical axis in order to avoid the shading of the lower panels connected to the –Z face. There is a specific mechanical subsystem for this rotation that uses a torsion spring, which allows installation of a sun sensor for the attitude. Final configuration with deployed panels modifies inertia properties of the satellite significantly increasing the inertia moment along the Z axis allowing a possible spin stabilized attitude around this axis. Final results show that it is possible to have a maximum available surface area that varies between 895 and 2,700 cm^2 for 1U and 3U CubeSats, respectively, and in terms of power, a value between 30 and 100 W (depending on the efficiency of the solar cells).

Babuscia et al. (Ref. 33) investigate the possibility of developing deployable, noninflatable antennas compatible with CubeSat dimensions and constraints. Their research provides potential answers on the possible dimensions for an inflatable antenna for small satellites, on the gain and resolution that can be achieved, and on the deployment and inflation mechanism compatible with CubeSat.

Greenbaum et al. (Ref. 34) have developed an optical moon baffle for stray light attenuation for use on ExoplanetSat, a 3U CubeSat being developed jointly by the Massachusetts Institute of Technology (MIT) and Draper Laboratory that aims to detect transiting exoplanets via precision photometry. They discuss the optical and mechanical design of the baffle, as well as the optical performance as demonstrated through the test of a prototype. The baffle collapses to fit into a small volume around ExoplanetSat's lens and deploys on orbit to a full length of 12 cm. The baffle is capable of attenuating moonlight by a factor of 105 at a lunar exclusion angle of 30°.

Zhang and Zhou (Ref. 35) utilized an electromagnet to develop a fast-response door release mechanism for the CubeSat Star of Aoxiang, by resetting a spring at the time of power off and unlocked by electromagnetic force at the time of power on. The measurement values agreed well with their simulation results and showed that the unlocking time was 41.2 ms and the current was 2.2 A and the energy consumption was only 2.5 J at the typical voltage of 28 V. On the condition of mechanical and thermal vacuum ground environment and down-deflection of ±5 V, the electromagnet door release mechanism could lock and unlock reliably. The proposed door release mechanism was successfully applied to unlocking and launching the Star of Aoxiang on orbit.

Benedetti et al. (Ref. 36) conducted a study to access a CubeSat's ability to complement an interplanetary scientific mission. More specifically, they investigated the AIDA (Asteroid Impact and Deflection Assessment) mission, an ESA and NASA joint effort to demonstrate the kinetic impact technique to change the motion of an asteroid in space. Their study shows that CubeSats can be successfully integrated as multiplatform systems to provide useful support to interplanetary missions. They provide a useful framework for the design and development of interplanetary CubeSat missions.

Santoni et al. (Refs. 37 and 38) investigate the limitations of available onboard power of CubeSats. These reports describe the design and realization of an enhanced deployable solar panel system for CubeSats that focused on system modularity. The system developed is the basis for a SADA (Solar Array Drive Assembly), in which a maneuvering capability is added to the deployed solar array in order to follow the apparent motion of the Sun. They compared different deployment concepts and architectures, leading to the final selection for their modular design. The deployment system is based on a plastic fiber wire and thermal cutters, guaranteeing a suitable level of reliability. The maximum power delivered by the system is about 50.4 W, which increased CubeSat solar array performance at the time it was designed.

Hong et al. (Ref. 39) conducted an early feasibility study using two deployer spacecraft, both moving on polar Earth orbits. They outline a proof-of-concept single-stage propulsion system that provides necessary propulsive input for the velocity change needed for the orbital inclination change of CubeSats. A series of illustrative simulations are given to demonstrate that sufficient and effective coverage of the Earth is achieved using the designed CubeSat constellation.

Sauder and Thomson (Ref. 40) developed a Ka-band high-gain antenna that could provide a 10,000-time increase in data communication rates over an X-band patch antenna and a 100-time increase over state-of-the-art S-band parabolic antennas. Their Ka-band parabolic deployable antenna (KaPDA) design aims to solve conflicting mechanical requirements on surface accuracy, stowed space, and ability to deploy. They used folding ribs to fit in the stowage space, deep rib sections with precision hinges to maintain surface accuracy, and a combination of an innovative inflating bladder and springs to deploy the antenna. RF simulations show that after losses, KaPDA would have about a 42-dB gain, at 50-percent efficiency. KaPDA could potentially create opportunities for a host of new CubeSat missions by allowing high data rate communication that would enable using data-intensive instruments or venturing further into deep space, including interplanetary missions.

Kuwahara et al. (Ref. 41) investigated small-satellite space debris that could affect current and future CubeSat activities. They concentrated on debris prevention and reduction methods. They also initiated a development activity of sail deployment mechanisms in order to deorbit the used microsatellite mainly by means of the residual atmospheric drags. The mechanism has a cylindrical form and utilizes unique deployable booms that can be folded down very compactly. Three different sizes were developed, and their functionalities were verified. The important characteristic of this mechanism is that the size of the sail can be modified very easily depending on the requirements of the spacecraft. Preparing different size sails, this kind of deorbit mechanism can become the standard prevention and reduction measures of space debris.

Crisp, Smith, and Hollingsworth (Ref. 42) investigated the development of distributed systems or constellations of small satellites. Two strategies were discussed in this report, which have the potential to significantly increase the viability of small-satellite constellations in Earth orbit. Deployment using natural Earth perturbations to indirectly achieve plane separations is analyzed using a developed method and compared to deployment utilizing the Earth-Moon Lagrange point L1 as a staging area prior to return to LEO. The analysis of three example missions indicates that these two strategies can facilitate the successful establishment of small-satellite constellations in Earth orbit, while also reducing propulsive requirements, system complexity, and/or cost. The study also found that the method of nodal precession is sensitive to the effects of orbital decay due to drag and can result in long deployment times, and the use of Lunar L1 is more suitable for constellation configurations where several satellites are present in each orbital plane.

Budianu et al. (Ref. 43) investigated intersatellite links for ensuring the success of CubeSat swarm missions. Nevertheless, it has hardly been considered until now. Depending on the type of application, required data rates can go up to tens of megabits per second, while power consumption and physical size are limited by the platform. The proposed communication scheme will combine power-efficient modulation and channel coding with multiple access and spread spectrum techniques, enabling the deployment of multiple satellites. They designed an antenna system such that links can be established and maintained independent of the satellites' orientation. An electrically steerable radiation pattern is achieved by placing antennas on each face of the cube. Conformal beamforming provides the system with 5 dBi gain for any desired direction of transmission, eliminating the need for attitude control. In addition, using planar antennas reduced the complexity of the mechanical part as they require no deployment.

Lim et al. (Ref. 44) discuss the challenges of the student-built VELOX–I nanosatellite as well as an alternative solution. The VELOX–I development process was improved through the past picosatellite development and operation experience. These challenges include the in-house design deployment mechanism, optical extension tube, multilayer insulator, and impact of 3U CubeSat structure on the communication system. Each design is required to meet several requirements such as operating temperature, overall thickness, and satellite mass. The success of VELOX–I ground contact and primary payload mission has proven the flight heritage of their presented design solutions.

Manohar and Rahmat-Samii (Ref. 45) utilized umbrella reflectors as an option for CubeSat missions. The umbrella reflector's surface consists of a discrete number of parabolic ribs that are connected through surfaces called gores. The gores cause the surface to deviate from that of an ideal paraboloid causing phase deviations in the aperture, ultimately leading to reduced gain. The choice of the number of ribs is a critical design consideration for CubeSat antenna designs as it provides the balance between mechanical complexity and RF loss. They analyzed umbrella reflectors with the intent of developing a relationship between the gain loss, parameters of the umbrella reflector (number of gores, aperture, diameter, and rib focal length), and frequency. Combining the root-mean-square error from the best-fit approach and Ruze's equation, it was shown that the gain loss scales are (√D/Ng)4 for a given Fr/D and frequency. The effects of amplitude taper were also incorporated into analysis. The validity of the closed-form expressions was shown through comparisons with physical optics' simulations.

Dolan et al. (Ref. 46) discuss a student-led sounding rocket experiment, StrathSat–R, which was supposed to be used to test novel inflatable structures in space conditions. The experiment aimed to test novel inflatable space technology in milligravity and micropressure conditions. It consisted of three distinct sections, the ejection housing on the rocket and two ejectable modules that are based on a CubeSat architecture measuring 10 by 11 by 13 cm. Shortly before reaching apogee, the two satellites were going to be ejected from the rocket and deploy their individual inflating structure during free flight. However, on May 9, 2012, the StrathSat–R experiment was launched onboard the sounding rocket REXUS 13 (Rocket Experiments for University Students 13) but failed to be ejected due to a procedure error.

Pirat et al. (Ref. 47) study two in-orbit demonstration (IOD) missions using CubeSat technologies. These IODs aim at alleviating the technical risk inherent to new technologies required for active debris removal (ADR) of large space objects, by using small and low-cost CubeSat systems. This report demonstrates how mission design and Guidance, Navigation, and Control (GNC) can serve the verification of navigation sensors performances as well as the validation of uncooperative debris capture using a net. Each mission is composed of a chaser and a target. The former being an 8U CubeSat and the latter a 4U, launched together in a 12U deployer. Both satellites are three-axis attitude controlled. The chaser has, in addition, three degrees of freedom (DOFs) translation capability using 1-mN cold-gas thrusters. Both CubeSats utilized Global Navigation Satellite System receivers to assist in the determination of range and relative velocity. This system provides a reference validation for the rotational vibration sensors. The relative position and velocity to be controlled are fully observable. Based on the mission design, various close inspection configurations were demonstrated. Both missions are analyzed using a six-DOFs simulator. Current issues and limitations of the CubeSat GNC are discussed, as well as conclusions regarding the feasibility of such missions.

Chahat et al. (Ref. 48) describe a deployable Ka-band antenna folding in a 1.5U (10 by 10 by 15 cm) stowage volume suitable for 6U- (10 by 20 by 30 cm) class CubeSats. This antenna is designed for telecommunication and is compatible with the NASA Deep Space Network (DSN) at Ka-band frequencies (uplink: 34.2 to 34.7 GHz and downlink: 31.8 to 32.3 GHz). Detailed simulations show that 42.0-dBi gain and 57-percent aperture efficiency is achievable at 32 GHz.

Kuwahara et al. (Ref. 49) describe a CubeSat debris prevention and reduction activity in order to provide safe space development and exploration activities in the near future. They launched the SpriteSat (Rising–1) in 2009 as well as the RAIKO CubeSat in 2013. Their activities include the development activity of sail deployment mechanisms in order to deorbit the used microsatellite mainly by means of the residual atmospheric drags. The mechanism itself has a cylinder form and utilizes unique deployable booms that can be folded down very compactly. The stored thin film inside the mechanism is pulled out of the case by the deployment force produced by the booms. Three different sizes of models have been developed, and their functionalities are verified. The important characteristic of this mechanism is that the size of the sail can be modified very easily depending on the requirements of the spacecraft. Preparing different size sails, this kind of deorbit mechanism can become the standard prevention and reduction measures of space debris. This report describes the development and qualification results of these mechanisms.

Levchenko et al. (Ref. 50) conducted a review on the rapid evolution of miniaturized, automatic, robotized, function-centered devices in space technology as reported in the international workshop Micropropulsion and CubeSats (MPCS–2017). They outlined the critical challenges that are faced by all CubeSat users. This focused review aims to highlight the most promising developments reported at MPCS–2017 by leading world-reputed experts in miniaturized space propulsion systems. Recent advances in several major types of small thrusters including Hall thrusters, ion engines, helicon, and vacuum arc devices are presented, and trends and perspectives are outlined.

Balinov (Ref. 51) discusses a project titled "FlyMate", which is the Lyon femtosatellite orbital deployer research project whose aim was to develop a reliable low-cost deployment mechanism for three or more CubeSat units. They investigated an orbital deployer that will have the possibility of sequential ejection of the satellites and ejection speed adjustment depending on the mission.

Park et al. (Ref. 52) investigated a constellation deployment method using plasma drag. The orbit decay rate of the satellites in a constellation is controlled using plasma drag in order to achieve a desired phase angle and phase angle rate. A simplified one-dimensional (1D) problem is formulated for an elementary analysis of the constellation deployment time. Numerical simulations are further performed for analytical analysis assessment and sensitivity analysis. Analytical analysis and numerical simulation results both agreed that the constellation deployment time is proportional to the inverse square root of magnetic moment, the square root of desired phase angle, and the square root of satellite mass. CubeSats ranging from 1U to 3U (1- to 3-kg nanosatellites) were examined in order to investigate the feasibility of plasma drag constellation on nanosatellite systems. The feasibility analysis results show that plasma drag constellation is feasible on CubeSats, which opens up the possibility of implementing plasma drag techniques for CubeSat constellation missions.

Fernandez et al. (Ref. 53) investigated research underway at NASA that is focused on the development of lightweight deployable thin-shell composite booms for small-spacecraft applications. Small CubeSat-class solar sails are a particular applications interest for this technology. Recently, 7-m composite booms were fabricated and integrated into a new 85-m^2-class square-solar-sail system suitable for use on 6U CubeSat spacecraft. Efforts to scale the boom fabrication processes to 14-m booms for a 12U, 360-m^2-class deep space solar sail are also underway. This report provides an overview of new solar sail structures and materials technologies being developed for these classes of small-satellite deep space missions. Key research and development efforts for 6U- and 12U-class composites-based solar sail systems are presented, including deployable composite boom development activities, boom deployment mechanisms design, solar sail membrane materials and testing, and ground deployment testing systems.

Lund (Ref. 54) discusses a technology readiness level experiment to ascertain the feasibility of deploying a conical, helical, wideband radar antenna from a CubeSat on board a REXUS sounding rocket flight. The experiment aimed to deploy the 80-cm antenna from a 1U CubeSat, strain rigidize the structure, measure the radiofrequency emissions, then eject the antenna and inflation system. The antenna was designed as a composite of aluminum and polyimide film with a polyurethane bladder to be strain rigidized in order to ensure structural stability of the inflatable. The outer layer of the antenna composite was polyimide film, while the inner was alternating helical strips of polyimide and aluminum. When fully pressurized, the aluminum is plastically deformed, while the polyimide remains in its elastic region. Upon depressurization, the two materials will return to different equilibrium lengths, resulting in a pre-tensed, rigid, structure. The experiment flew on the REXUS sounding rocket and reached an apogee of approximately 80 km. Analysis has shown that all systems performed successfully. Video analysis showed complete deployment and ejection, while RF measurements indicate an estimated 75-percent antenna efficiency.

Dewalque, Rochus, and Brüls (Ref. 55) discuss the importance of structural damping in the dynamic analysis of compliant deployable structures. This report discusses the need for high-fidelity mechanical models in order to get a detailed understanding of the deployment process, improve the design, and predict the actual behavior in the space zero-g environment. These simulations could be successfully achieved because of the presence of numerical damping in the transient solver. They show that the dynamic simulation of a tape spring can be made less sensitive to numerical parameters when the structural dissipation is taken into account.

Harkness et al. (Ref. 56) describe a prototype CubeSat module to deploy a gossamer aerobrake, using strain stored in tape springs at end of life. They proposed a hub geometry to reduce bending shock at end of deployment while simultaneously permitting radial, as opposed to tangential, deployment. The revolutions per minute of the hub is measured under various deployment conditions to verify the system, while high-speed photography is used to characterize the behavior of the tape spring during unspooling and contrast it to the behavior of a traditional tangential deployment system. They also developed a unique folding pattern of the membrane, which takes advantage of the symmetrical deployment offered by the petal hub, and the unfolding mechanism is verified by numerical and experimental analysis.

Svitek et al. (Ref. 57) discuss the LightSail–1 (launched in 2015), which is the beginning of a program proposed by The Planetary Society to launch three separate spacecraft over several years. The objectives of LightSail–1 include the ability to manage orbit energy as well as control the spacecraft under the power of the solar sail. LightSail–1 demonstrated key technologies including sail deployment, sail material management during flight, and gossamer structure dynamics. The LightSail–1 is a 3U CubeSat, two-thirds of which will contain the sail material, deployment mechanism, and payload, with the avionics taking up the rest of the volume. It deploys a 32-m^2 sail made up of four quadrants in a cruciform arrangement requiring a set of four 4-m booms. The spacecraft is actively controlled with magnetic torquers and a momentum wheel. Orbit raising will require two rapid 90° slew maneuvers every orbit that are accomplished with the momentum wheel. LightSail–1 was designed to provide the building blocks for the design of LightSail–2 (launched in 2019) and LightSail–3.

Bui et al. (Ref. 58) highlight the design approach, challenges, and solutions during the development of VELOX–I nanosatellite. VELOX–I was developed by Nanyang Technological University (NTU) for technology demonstration of an in-house-built camera, GPS, and intersatellite communication payloads. The mission requires an innovative design to miniaturize the subsystems and extend the capability of the standard 3U CubeSat. They discuss an attitude control subsystem, the deployable optics, and the piggyback picosatellite VELOX–PIII and its deployment mechanism. This satellite was launched into LEO in June of 2014. The design of structure, deployment mechanism, and thermal control of VELOX–I has been validated by analyzing the satellite's housekeeping data.

Worrakul et al. (Ref. 59) present a conceptual design and development of a 1U CubeSat named "KNACKSAT" (KmutNb (King Mongkut's University of Technology North Bangkok) Academic Challenge of Knowledge SATellite). The main functions of the satellite include transmitting housekeeping data through a continuous wave, sending uplink commands and downlink data through radiofrequencies, and taking images by using a complementary metal-oxide semiconductor camera. KNACKSAT consists of seven subsystems: (1) electrical power, (2) camera (or payload), (3) structure, (4) command and data handling, (5) attitude determination and control, (6) communication, and (7) deployment control. Results of a functional integration test of the subsystems through TableSat are also presented.

Araromi et al. (Ref. 60) discuss the CleanSpace One (CSO) microsatellite to mitigate debris in space, which is an ever-increasing problem for spacecraft in Earth orbit. Its mission is to perform active debris removal of a decommissioned nanosatellite (the CubeSat SwissCube). An important aspect of this project is the development of the gripper system that will entrap the capture target. They present the development of rollable dielectric elastomer minimum energy structures (DEMES) as the main component of CSO's deployable gripper. DEMES consist of a prestretched dielectric elastomer actuator membrane bonded to a flexible frame. The actuator finds equilibrium in bending when the prestretch is released and the bending angle can be changed by the application of a voltage bias. The inherent flexibility and lightweight nature of the DEMES enable the gripper to be stored in a rolled-up state prior to deployment. Proof-of-concept actuators of three different geometries using a robust and repeatable fabrication methodology were fabricated. The resulting actuators were mechanically resilient to external deformation, and display conformability to objects of varying shapes and sizes. Actuator mass is less than 0.65 g and all the actuators presented survived the rolling-up and subsequent deployment process. They demonstrated a maximum change of bending angle of more than 60° and a maximum gripping (reaction) force of 2.2 mN for a single actuator.

Wilke, Schraml, and Heberling (Ref. 61) discuss LDA and their surface accuracy, especially at high operating frequencies. The concept described in this report is to use the drag sail deployment technique and use the expanded membrane surface as a reflector antenna. The effects of the surface errors, which are inevitably introduced by the mechanics, are studied to help determine a break-even point between antenna performance loss and cost reduction compared to a conventional LDA. Possible applications are small satellites like CubeSats, which could enhance their communication link budget by deploying a medium performance but low-cost LDA.

Arute et al. (Ref. 62) detail Project POPACS (Polar Orbiting Passive Atmospheric Calibration Spheres), which uses a 3U Canisterized Satellite Dispenser (3U CSD) and launched three 10-cm-diameter spheres of different masses (1, 1.5, and 2 kg). These spheres were to be tracked to measure changes in the density of the upper auroral atmosphere in response to solar stimuli. Also, because the 3U CSD is designed for use with CubeSats, a suspension and deployment mechanism was designed to ensure the spheres do not come in contact with each other or the CSD. They presented the designs selected to mitigate the concerns and enable the mission to proceed as desired: a sphere assembly with threaded halves for mating, and the spring-loaded "banana peel" suspension and deployment mechanism.

Arita et al. (Ref. 63) proposed a new available deployable structure called Deployable Cube, which is a bistable structure applying buckling actively. They developed a prototype of the Deployable Cube for a CubeSat. They investigated the structural properties by performing Eigen mode analysis after deployment of the prototype model was performed, and the stiffness was indicated. Dynamic buckling analysis using the original method proposed was also carried out for the initial stage of the deployment and it is indicated that the estimation of buckling mode is valid.

Lei et al. (Ref. 64) discuss a prototype deployable space telescope based on tape springs. Their deployable telescope is composed of a primary mirror assembly, a secondary mirror assembly, six foldable tape springs to support the secondary mirror assembly, a deployable baffle, aft optic components, and a set of lock-released devices based on shape memory alloys. The deployment errors of the secondary mirror of a space telescope are measured with a three-coordinate measuring machine to examine the alignment accuracy between the primary mirror and the deployed secondary mirror. Modal identification is completed for the telescope in the deployment state to investigate its dynamic behavior with impact hammer testing. The results of their experimental modal identification agree with their finite element analysis.

Christodoulou et al. (Ref. 65) discuss deployable multifunctional reconfigurable antennas that offer more DOFs to future CubeSat applications than existing antenna technology. The ability of these new antennas to modify their geometry and behavior in order to adapt to changes in environmental conditions or mission requirements offers more possibilities for space communications requirements. The idea is to dynamically change the functionality of the antenna without increasing the real estate required on a satellite platform. The same antennas can also be used not only for communication and remote sensing purposes but also for RF harvesting.

Bellini et al. (Ref. 66) discuss cleaning up space debris with a debris "cleaner kit" based on polyeretanic foam. They define multiple properties of polyeretanic foam in different compositions, defining two different systems that can be integrated into a small cleaner kit for debris removal. The first system consists of a drag sail composed of a specific foam formulation that can guarantee a compact storage volume and a passive deploying system without complex mechanisms or booms that could be origins of failures. The second system consists of a device that allows generating the foam and using it like glue between the cleaner kit and the debris. Through several thermal, vacuum, and adhesion tests, it was possible to define a specific chemical formulation that permits the correct reaction time and the suitable mechanical properties to create a rigid link with the cleaner satellite. Once the link has been accomplished, it is possible to act on the debris controlling the deorbiting maneuver with a propulsion system or by exploiting the drag sail. The kit has been designed in order to leave the maximum flexibility depending on the kind of mission.

Santoni, Piergentili, and Ravaglia (Ref. 67) describe a collision probability analysis for a nanosatellite cluster deployment, performed by a series of Monte Carlo simulations and comparing the results obtained with different release mechanisms, procedures, and orbital dynamics modeling assumptions. The model used for the analysis is based on the Encke equations for relative motion, considering the main perturbations acting on the satellites, such as Earth gravitational field higher harmonics, Moon and Sun third-body perturbations, solar radiation pressure, and atmospheric drag. The risk of collisions is assessed performing Monte Carlo simulations based on the numerical integration of the equations of motion. The final results provide the collision probability assessment and the influence that the release device configurations have on this risk.

Wu et al. (Ref. 68) present a study on the implementation of a flexible deployable heat shield that passively deploys and stiffens due to centrifugal forces generated from a self-regulated autorotation. They demonstrate that the heat shield is similar to a proportional-integral-controlled second-order nonlinear system. The heat shield design offers a capability to actively adjust the deployment using conventional attitude control devices. This operation is explored by simulating the reentry of a CubeSat-sized vehicle equipped with an off-the-shelf reaction wheel controlled by a switching phase shift controller and gain-scheduled controllers. The effects of the control parameters are investigated and successful oscillation suppression as well as an open-loop downrange maneuver of over 300 km is predicted for reentry from LEO.

Li et al. (Ref. 69) investigate potential strategies to stabilize a nanosatellite platform with a space camera and integrated mechanical parts. The deployed mirror system used a diamond turned mirror for the initial prototype as an off-axis paraboloid. The mechanisms for mirror systems may use methods like miniature geared motors, stiction motors, and shape memory alloy hinges. A closed-loop control of the mirror position was used to iterate to a fully aligned system. Following an initial baseline to establish current state of art based on both in-orbit performance and off-the-shelf subsystems available to the market within the constraints of a 3U nanosatellite system, a number of feed-forward or feedback control loops and sensor systems are studied to determine a simple process for compensating for the motion.

Yamagiwa et al. (Ref. 70) attempted to verify two basic technologies required for space elevators using microsatellites: the tether (cable) deployment technology and the climber operation along the tether in space. Tether deployment is performed by a CubeSat called STARS–C (Space Tethered Autonomous Robotic Satellite—Cube), which was released from the Japanese experimental module Kibo on ISS early in 2017. STARS–C consists of a mother satellite (MS) and daughter satellite (DS) connected by a 100-m tether. Its mission is focused on the tether deployment for studying the tether dynamics during the deployment with the goal of improving the smoothness of such deployment in future tether missions including space elevator. The MS and DS have common subsystems, including power, communication, and command and data handling systems. They also have a tether unit with spool and reel mechanisms as a mission system. In addition, they have been designing the next-step microsatellite called STARS–E (Space Tethered Autonomous Robotic Satellite—Elevator), which is a 500-mm size satellite intended to verify the climber operation in space. It consists of a MS and DS jointed by a 2-km tether and a climber that moves along the tether. STARS–C was launched in December of 2016.

Omar, Guglielmo, and Bevilacqua (Ref. 71) have developed a drag deorbit device (D3) for CubeSats consisting of retractable tape-spring booms that provide a drag area of 0.5 m^2 and can deorbit a 12U, 15-kg CubeSat from a 700-km circular orbit in 25 yr. By modulating the D3 drag area, orbital maneuvering can be performed, and the host satellite can be made to deorbit in a desired location. They detail the design of a 2U CubeSat and mission that will be launched to validate the D3 and the orbital maneuvering, targeted reentry, collision avoidance, and attitude stabilization algorithms developed by the Advanced Autonomous Multiple Spacecraft (ADAMUS) laboratory. The targeted reentry and orbital maneuvering algorithms have been tested extensively through Monte Carlo simulations and collision avoidance algorithms are currently in development. The CubeSat will consist of a standard 1U structure containing a power system, battery, GPS, UHF radio, and D3 control board with the D3 subsystem mounted to the back to achieve a 2U form factor. Radar tracking data along with GPS telemetry will be utilized to characterize the performance of the system and algorithms, update reentry aerothermodynamic models, and gauge the effectiveness of atmospheric density estimation techniques.

Sinn et al. (Ref. 72) proposed to design and build an initial prototype of an all-inflatable satellite with disaggregated electronics for deployment onboard a Balloon Experiments for University Students (BEXUS) balloon as proof of concept. The idea is to use inflatable cell structures as support for all the subsystems composing a typical nanosatellite. Each subsystem and component were mounted on a different cell. Cells are both individually inflated and controlled. The aim was to design and build an inflatable satellite, demonstrating the deployment, communication among components, and local control enabling structure shape adaption via soft robotic actuators and micropumps. The experiment deployed two inflatable structures made of 5 by 2 cells that are packed in a 10- by 10- by 10-cm CubeSat reaching a size of 70 by 18 by 14 cm once deployed. Flexible circuitry was used to mount all the electronic subsystems on the surface of the folded inflatable. The experiment was flown onboard the BEXUS 16 stratospheric balloon to an altitude of 29 km for 2 to 5 h from the Swedish ESRANGE Space Center in October of 2013.

Santoni et al. (Ref. 73) discuss a steerable deployed solar array system for 1- to 5-kg weight nanospacecraft designed to enhance the achievable performance of CubeSats. The system proposed is a modular one and suitable in principle for the 1U, 2U, and 3U standard CubeSat bus. The size of each solar panel is the size of a lateral CubeSat surface. A single DOF maneuvering capability is added to the deployed solar array in order to follow the apparent motion of the Sun as close as possible. The system design tradeoff is discussed, comparing different deployment and motion control concepts and architectures, based on single- or double-motor implementations. The system validation is based on numerical simulations and prototype testing, showing the possible enhancements offered by the system in typical mission scenarios.

Asundi, Bhagatji, and Taylor (Ref. 74) present a multifunction drag enhancement and measurement system (mDEMS) to rapidly deorbit containerized Pico/Nano/Micro-Satellites (PNMSats) in order to mitigate space debris. Their goal is to rapidly deorbit PNMSats at the end of their mission life and validate and refine drag-temperature models. A computer-aided mechanical design is presented, which demonstrates the integration of a telescopic boom for isolating the onboard magnetometer from electromagnetic interference, a drag gossamer mounted with drag sensors on a flexible printed circuit board (PCB), a container for storing batteries, and a dipole UHF/VHF (very high frequency) antenna. The mDEMS is a two-stage deployment system for PNMSats in altitudes of up to 600 km.

Underwood et al. (Refs. 75 and 76) describe the InflateSail (QB50–UK06) CubeSat, designed and built at the Surrey Space Centre (SSC). This 3.2-kg 3U CubeSat was equipped with a 1-m long inflatable mast and a 10-m^2 deployable drag sail. InflateSail's primary mission was to demonstrate the effectiveness of using a drag sail in LEO to dramatically increase the rate at which satellites lose altitude and reenter the Earth's atmosphere and it was 1 of 31 satellites that were launched simultaneously on the Polar Satellite Launch Vehicle (PSLV) C–38 from Sriharikota, India, in June of 2017 into a 505-km, 97.44° Sun-synchronous orbit. This report describes the results of the InflateSail mission, including the observed effects of atmospheric density and solar activity on its trajectory and body dynamics. It also describes the application of the technology from the RemoveDEBRIS project and its potential as a commercial deorbiting add-on package for future space missions.

Paiano et al. (Ref. 77) discuss developing launch services, GAUSS Srl, which is a launch platform to deploy in-orbit DSs. Two missions have already been successfully performed allowing the deployment in orbit of the first four PocketQubes ever and eight CubeSats. Recently, the main platform structure has been updated in order to include more deploying mechanisms and to offer services to different shaped satellites such as CubeSats, TubeSats, and PocketQubes to optimize the satellite distribution mass. The analysis was not limited to the satellite bus alone but included the nanosatellites boarded inside the deployment mechanisms as well. They developed a finite element model that considered a sandwich panel structure made of two different materials: sandwich aluminum-aluminum and carbon fiber-aluminum. The model used for analysis and simulations was based on a finite element method software and the dynamic loads adopted as input for the simulations are those established by the launch provider. This report gives an overview of platform design and structural modeling, showing the results achieved through the finite element method analysis and how they have guided the design in terms of dimensions and material selection. Particular attention is given to the analysis of normal frequencies and modal shapes related both to the main platform and to the deployment mechanisms boarded inside the carrier.

Yamagiwa et al. (Ref. 78) discuss verifying two basic technologies of a space elevator by using microsatellites to obtain data for a future tether deployment technology and combine this with climber operation designs. STARS–C is a CubeSat for the verification of tether deployment in space and was released in December of 2016 and is currently in operation. STARS–E is a 500-mm size satellite to verify the climber operation in space. STARS–E is planned to deploy a 1,000-m tether and is required to cope with the strict requirement for a debris safety standard to perform its mission. The plan is to utilize STARS–E and STARS–C CubeSat missions to accelerate space elevator research and development in the future.

Forshaw et al. (Ref. 79) provide an overview of the ADR activities at the SSC, focusing on four in-orbit missions. The European Commission (EC) Seventh Framework Programme (FP7) RemoveDEBRIS mission was launched in 2018 and aimed to demonstrate key technologies for ADR by performing in-orbit demonstrations representative of an ADR mission (net and harpoon capture and vision-based navigation), drawing on the expertise of Airbus DS (U.K., Denmark, and France) and Surrey Satellite Technology Limited (SSTL). The EC FP7 DeOrbitSail project launched in 2015 involved the in-orbit test of a deployable system for satellite afterlife disposal, consisting of an SSC aluminized Kapton® (DuPont™) sail of 4 by 4 m deployed by a motor and four German Aerospace Center (DLR) carbon-fiber-reinforced plastic (CFRP) booms. They also discuss the DEPLOYTECH and QB50 InflateSail CubeSat missions whose payloads consisted of a 10-m^2 drag-deorbiting sail, and a 1-m long inflatable rigidizable mast used as a technology demonstrator satellite for the QB50 mission.

Santoni et al. (Ref. 80) discuss an orientable deployed solar array system for a 1- to 5-kg nanospacecraft. The goal is to enhance the achievable performance of these typically power-limited systems. They proposed a modular system that is suitable, in principle, for the 1U, 2U, and 3U standard CubeSat bus. The size of each solar panel is the size of a lateral CubeSat surface. A single DOF maneuvering capability is given to the deployed solar array in order to follow the apparent motion of the Sun as close as possible, given the mission requirements on the spacecraft attitude. The system design tradeoff is discussed, leading to the selection of an architecture based on two independently steerable solar array wings.

Pankow and White (Ref. 81) discuss a deployable carbon fiber boom that was designed and tested to show feasibility at the CubeSat scale. Prototype booms with a lenticular cross section were developed in conjunction with a computational model. Mechanical testing indicated the ability to reliably flatten the booms in a bistable configuration so that they can be stored on a reel.

Costantine et al. (Ref. 82) propose two UHF antenna concepts to be deployed on a CubeSat platform. Both antennas display logarithmic periodicity in their structure. The first antenna proposed is the conical logarithmic spiral antenna, while the second is the logarithmic periodic crossed dipole antenna array. The design of these antennas, as well as their deployment mechanisms, were presented.

Zaki et al. (Ref. 83) present an approach to design a feasible and reliable monopole antenna deployment mechanism for BIRDS–2 CubeSat applications. They discuss detailed results of the mechanical and electrical interfaces of the two monopole antennas deployment mechanism with the satellite body and the nichrome wire burning release mechanism analysis. The test results of the mechanism were analyzed particularly on the deployment time and the nichrome wire temperature differences.

Grzesik et al. (Ref. 84) discuss the Optical Coatings Ultra Lightweight Robust Spacecraft Structures (OCULUS) project whose goal is to develop a high-quality metallization process for surface modification of high-precision CFRP structures. This report introduces a detailed overview of the demonstrator design with special focus on the mechanism that deploys and aligns the primary and secondary mirror. A design tradeoff is summarized, and the dependencies of the mechanical positioning mechanism is discussed. They detail the design of the deployment and alignment mechanism with respect to the other satellite subsystems as well as the overall volume, mass, and energy budget. The positioning accuracy and resulting optical performance of the space telescope for Earth observation are estimated. They also describe a conceptual design to demonstrate the functionality of the deployment mechanism independently of the alignment mechanism in microgravity tests.

Baig (Ref. 85) describes the design and successful implementation of an integrated solar panel deployment mechanism using torsion springs and microlevers. The design is in accordance with CDS and also assures minimal extra mass and the best utilization of a three-unit CubeSat's area. This design is equally applicable to a single and double-unit CubeSat.

McGuire et al. (Ref. 86) present a deployment system design that creates a plane of solar panels to collect energy. The goal is to allow more panels to be in direct normal sunlight at any given point in conjunction with the onboard attitude determination and control system, facilitating increased power generation. The deployable system comprises a PCB holding the solar cells, which are attached to an aluminum hinge. The efficiency of this approach for power generation is compared to other perspective approaches.

Blandino et al. (Ref. 87) present the development of a general automated process using multibody dynamics software (RecurDyn; FunctionBay, Inc.) to efficiently take a detailed hinge assembly model and simulate its range of motion while retrieving stiffness information for all DOFs. A vertical software application is presented that characterizes and simplifies the hinge model and allows the simplified model to be integrated easily into a solar array system model. The described techniques and vertical application can potentially be applied to a wide range of deployable space structures.

Jeon and Murphey (Ref. 88) discuss a meter-class deployable boom featuring a single burn wire release mechanism and motorless deployment actuation by the stored strain energy of bistable tape springs. At the end of deployment, the tape springs lock out to remove the deployment DOF from the structure while providing structural stiffness, derived from the two inwardly facing and offset bistable tape springs, spanning from end to end. The presented device has stowed dimensions measuring 5.0 by 3.8 by 3.8 cm, well within the packaging requirements of a 1U CubeSat. The mechanical design and deployment properties are investigated and presented.

Chahat et al. (Refs. 89, 90, and 91) present a mesh deployable Ka-band antenna design that folds in a 1.5U (10 by 10 by 15 cm) stowage volume suitable for 6U-class (10 by 20 by 30 cm) CubeSats. Detailed simulations and measurements show that 42.6-dBi gain and 52-0 aperture efficiency are achievable at 35.75 GHz. The mechanical deployment mechanism and associated challenges are described and both solid and mesh prototype antennas were developed, and measurement results show agreement with simulations.

Pignatelli (Ref. 92) investigates the use of finite element models for rail-type CubeSat deployers. Models for a 3U deployer were developed and compared to experimental results to determine how accurately dynamic loads can be predicted in rail-type deployers with isolation. Analysis methods are refined with the intent of applying to a 6U deployer when test data is available. The results indicate that this system can be accurately modeled to provide predictable environments to CubeSat payloads.

Babuscia et al. (Ref. 93) discusses an inflatable antenna for CubeSats and investigates the design and radiation model for the antenna. The report provides details of the antenna's fabrication and related issues as well as the mechanism to fold and deploy the antenna in space. It also proposes how to improve the fabrication process and the design of a 3U CubeSat mission.

Lehmensiek, Van Zyl, and Visser (Ref. 94) present the design, the deployment mechanism, and the measurement of a high-frequency (HF) antenna on a 1U CubeSat. A HF radio beacon on this CubeSat was used as a space-based signal source to contribute to the monitoring of the density and movement of the polar and high-latitude ionosphere making use of the interferometer antenna arrays at the South African Antarctic station, SANAE–IV.

Carandente and Savino (Ref. 95) discuss new concepts of deorbit and reentry modules for standard CubeSats. The concepts are mainly based on deployable, umbrella-like structures, useful to perform deorbit and reentry operations taking advantage from a substantial reduction of the ballistic coefficient.

Zander et al. (Ref. 96) discuss the risk for spacecraft in LEO utilizing a drag augmentation device that increases the drag-efficient surface of a satellite. They analyze this type of device that was flown on the DeorbitSail CubeSat. The goal was to demonstrate the in-orbit deployment of a 4- by 4-m drag sail, suitable for small- and medium-size satellites, as an end-of-life deorbiting device. They focus on one of the main structures, the deployable thin-shell CFRP booms that are susceptible to buckling. They provide information on the applicable loading on the booms derived by the space application, the used test stand, and equipment as well as the testing itself.

Fulton et al. (Ref. 97) discuss a high-strain composite, bistable-tape-spring-actuated, meter-class deployable boom developed and flight qualified at the Air Force Research Laboratory. This boom demonstrates new free-deployment technology enabled by high-strain composite materials and a minimal shroud design. A customized six-DOFs gravity offload system with bus and payload mass simulators was developed to enable full system dynamics testing. The boom passed all flight qualification testing, and results of the testing program are included.

Berthoud and Phillips (Ref. 98) present a study whose aim was to design a deployment system to deliver 50 or more CubeSats together. The study commenced with a review of the deployment mechanisms currently available, such as the P-POD, Tokyo Picosatellite Orbital Deployer (T-POD), eXperimental Push Out Deployer (XPOD), Innovative Solutions In Space Payload Orbital Dispenser (ISIPOD), CSD and Japan Aerospace Exploration Agency (JAXA)-Picosatellite Orbital Deployer (J-POD) systems, as well as auxiliary launch adapters. The aim was to be compatible with as wide a range of launchers as possible. Three design options were prepared to meet the design requirements: the "Cube," the "Tower," and the "H." Requirements and state of the art for the door opening and the delivery mechanism were also subject to a tradeoff. The design selected was that of the "H" deployment system. The "H" has a versatile structure with detachable auxiliary panels. It offers a capacity of 72 CubeSats in its standard configuration or 12 lots of 6U units in its alternate configuration. It is compatible with Vega, Soyuz, Rockot, and PSLV.

Pawlina and Yu (Ref. 99) discuss the problem of optimizing the energy tradeoff between the benefit of pointing a CubeSat's deployable solar panels at the Sun and the control effort required to do so. Their model assumed an unspecified three-axis attitude control actuator set that acts abstractly on the satellite bus rigid body, producing torques about the body's principal axes. Given that the orientation of the satellite face with respect to the Sun depends on orbit parameters, an orbit was chosen that allowed all dynamic aspects of the problem to be observed in simulation. The simulation returned suboptimal values of proportional derivative gains and showed that the solution is not the trivial edge case in which the solar panels are not articulated.

Sauder et al. (Ref. 100) discuss developing a large 1-m antenna operating at 35.75 GHz for radar applications. They chose a reflectarray design since it is compatible with the CubeSat form factor. Several iterations of the design were built and tested with a recent RF test of a fully deployed assembly demonstrating a gain of 48.0 dBi. Deployment repeatability tests at ambient conditions indicated initial success. The goal is to have the antenna flight ready by 2020.

Yasin and Santer (Ref. 101) investigate the use of ultrathin high-strain composite flexures that are suitable for incorporation in a simple z-folded deployable solar panel concept. To enable the design to be implemented, composite flexures fabricated from TR50S–K51 laminae are characterized in a sequence of tests, at both short- and long-duration timescales. They discuss how the use of high-strain composite tape springs instead of conventional torsion springs enables postdeployment reconfiguration of the solar panels via a buckling mechanism.

West et al. (Ref. 102) discuss a deployable carbon fiber boom that was designed and tested to show feasibility at CubeSat scale. Prototype booms with a lenticular cross section were developed in conjunction with a computational model. Mechanical testing has shown the ability to reliably flatten the booms in a bistable configuration so that they can be stored on a reel.

Babuscia et al. (Ref. 103) present a first attempt to develop an inflatable antenna for CubeSat applications. They provide input on the possible dimensions for an inflatable antenna for small satellites, the gain and resolution that can be achieved, and on the deployment and inflation mechanism compatible with CubeSat requirements. They also present a design of an antenna that can potentially achieve the required CubeSat performance metrics and constraints.

Park et al. (Ref. 104) present a spring-loaded pogo pin concept as a holding and release mechanism of solar panels for CubeSat applications. This spring-loaded pogo pin will serve as an electrical interface, a separation spring, and a status switch. The advantages are that such a mechanism includes an increased loading capability, negligible induced shock level, synchronous release of multiple panels, and handling simplicity during integration. A demonstration model of the mechanism was fabricated and functionally tested under various test conditions such as different input voltages, different numbers of tightened nylon wires, and different temperatures (ranging from –40 to 70 °C).

Khalifi and Fitz-Coy (Ref. 105) discuss the SwampSat II, which is a 3U CubeSat designed to collect and characterize very low frequency waves (VLF) in LEO in the 2- to 32-kHz frequency range. They present design analyses and simulations for several states from postlaunch tumbling through to deployment and operations to identify and select appropriate components for the attitude determination and control system components. Simulations based on a range of initial angular velocities representative of typical tipoff rates experienced by 3U spacecraft were performed to validate the feasibility of the mission's concept of operations.

Zhu (Ref. 106) proposed a mission design for a CubeSat flying with an electrodynamic tether (EDT) to achieve a set of engineering and scientific objectives. The basic mission involved two CubeSats connected by 100-m-long aluminum EDT. The engineering objectives of this mission were to perform a pioneering mission to demonstrate deployment and stabilization of an EDT with an end mass, current collection using bare EDT, field-effect electron emission, and spacecraft deorbiting by EDT technology. The details of nanosatellite designs for both the chief and deputy nanosatellites are explained.

Bewick, Colombo, and McInnes (Ref. 107) define a mission concept and system design for a 3U CubeSat technology demonstration. They proposed to transfer CubeSats from the release orbit into a LEO. The strategy proposed exploits the effects of atmospheric drag and solar radiation pressure to passively decrease the apogee altitude and increase the perigee altitude, respectively. This is achieved by deploying a lightweight balloon that increases the area-to-mass ratio of the spacecraft. Once orbit is reached, the spacecraft can be powered up again and the balloon is ejected to avoid rapid deorbiting. It is shown that the abandoned balloon is removed from orbit within weeks.

Costantine et al. (Ref. 108) present the design process and the deployment mechanism of a quadrifilar helix antenna and a conical log spiral antenna. They proposed to operate the two antennas in the UHF band. The deployment mechanisms for both antennas include helical pantograph and origami patterns such as Z-folding configurations. Both antennas are fabricated and tested for both deployment and radiation performance. A comparison is executed between both designs, and their potential deployment possibilities from CubeSats are also investigated.

Zhang and Zhou (Ref. 109) discuss the reliable deployment for the CubeSat Star of Aoxiang. A structure scheme of the kinematics system was proposed. It uses a disengaging spring to impulse the CubeSat for opening the cabin door and uses a spring pin to lock the door. They also conducted ground deploying tests for a prototype of the deploying mechanism. The experimental results show that the actual deployment process is similar to the numerical simulation. The downlink data indicate that initial deploying velocity is 1.08 m/s and three-axis angular velocity is less than 2 deg/s, meeting the requirements of initial deploying velocity and posture for CubeSats.

CubeSats and Power Generation

One of the main CubeSat bus limitations is the available onboard power. The maximum power obtained using body-mounted solar panels and advanced triple-junction solar cells on a triple-unit CubeSat is typically less than 10 W. Satellites and space application devices demand high efficiency with size, volume, mass, and losses reduced simultaneously due to low power generation in space orbit and the relation between mass and the overall space mission cost. The need to save energy is mandatory in all systems due to low power generation and reduced size.

Affordable and convenient access to electrical power is essential for all spacecraft and is a critical design driver for the next generation of CubeSats. The development of higher power generation system solutions that comply with P-POD stored energy restrictions during launch will increase the range of CubeSat missions. Since the power and energy demands of current CubeSats have increased dramatically, the need for larger deployable solar arrays, lower power electronics, efficient energy storage systems, and energy transfer and harvesting systems is in high demand. In terms of energy storage, more advanced battery chemistries with higher energy densities and higher power capabilities over a wider operating temperature range are also a fundamental need. What follows is an extensive review (Refs. 110 to 162) of CubeSat power generation research ranging from enhanced solar array configurations to optimizing experimental and modeling systems to new and innovative miniaturized power solutions. The selection of an appropriate energy storage system is driven by mission requirements related to power, energy, and lifetime (Ref. 112).

A CubeSat has only a limited surface area on which solar panels can be installed to generate power. The incidence angle of sunlight on the solar panels also varies according to the revolution and rotation of the satellite. These are important parameters for determining the amount of power that a CubeSat can generate (Ref. 136). For any CubeSat, the power system unit is designed to deliver the required energy so the nanosatellite can achieve its desired mission. Thus, the input energy for the solar panels and the output energy from the solar cells must be increased (Ref. 133).

The market of small satellites for educational, institutional, and commercial purposes is in rapid growth. In order to allow different mission scenarios, small-satellite platforms down to CubeSat units need versatile, low-cost, compact, and reliable power systems. This presents a design opportunity to develop various objective functions related to energy management and methods for optimizing these functions over a satellite design. Currently, the main component used to generate electric power is the solar panel. However, due to area restriction and low solar panel efficiency, other technologies are being studied to improve the overall power generation capacity in CubeSats.

Frohling (Ref. 110) discusses reducing the size of space-based power controllers through switching at higher speeds to address the need for miniaturized cooling solutions applicable to CubeSats.

Johnson et al. (Ref. 111) describe a Lightweight Integrated Solar Array (LISA) that was designed, prototyped, and tested at NASA Marshall Space Flight Center. The LISA provides an affordable, lightweight, scalable, and easily manufactured approach for power generation in space. It potentially has wide-ranging applications from serving small satellites to providing abundant power to large spacecraft in geosynchronous Earth orbit and beyond.

Chin et al. (Ref. 112) provide a general review of performance capabilities of state-of-the-art lithium-ion battery technologies as well as other advanced energy storage systems for small-satellite applications.

Rakow, Hedin, and Anthony (Ref. 113) introduced a new solar array technology known as the Composite Lightweight Array using Shape-memory Polymer (CLASP). The CLASP wing includes elastic memory composite hinge lines spanning its full width to enable tight packaging of a stowed CLASP wing and a controlled, damped deployment. They present a Z-folded, CLASP wing design currently in development and sized to generate 200 W+ power for a 6U CubeSat. They also present structural and thermal analysis of the wing performed with a high-fidelity finite element model. The CLASP wing is shown to have (>250 W/kg) specific power and low stowed volume (>300 kW/m^3) while maintaining high deployed stiffness and strength.

Ali et al. (Ref. 114) discuss power management tiles (PMTs) as they relate to CubeSat missions. They developed a single module for the CubeSat satellites, called CubePMT. The goal of their work was to implement these subsystems in a single module focusing on the main issues and adding some additional features. They performed a full set of tests and simulations and the results were in close agreement.

Dinelli et al. (Ref. 115) present an electric propulsion system called the microcathode arc thruster, which is a quad-channel microthruster subsystem used during the Ballistically Reinforced Communication Satellite (BRICSat–P) mission launched in 2015. They demonstrated that an electric propulsion system is capable of supporting CubeSat missions. They presented the design tradeoffs, model and simulation results of the flight hardware, and its expected performance on orbit.

SPIE (Ref. 116) published a collection of research papers on power generation applicable to CubeSats including the optimization of material and device parameters of CdTe photovoltaic for solar cell applications, a charging system using solar panels and a highly resonant wireless power transfer model for small unmanned aerial system applications, low-temperature processing of dielectric perovskites for energy storage, a piezoelectric-based hybrid reserve power source for munitions, and a CubeSat deployable solar panel system.

Uwarowa and Jaworski (Ref. 117) investigated the possible use of thermoelectric generators onboard small satellites without the use of radioisotopes. They proposed an integrated system that allows the harvesting of energy from a small thermoelectric generator onboard a 3U CubeSat as an example.

McTernan et al. (Ref. 118) discuss the feasibility of using an EDT to be used by satellites to harvest energy from orbital potential by using the Lorentz force interactions with the geomagnetic field. They surmise that small EDT systems the size of CubeSats have the potential to produce more energy than mounted solar panels alone and provide a unique solution to the satellites' energy and propulsion needs throughout the size and mass spectrum of current and future technology.

Scharlemann et al. (Ref. 119) summarize the theoretical and experimental efforts to develop a miniaturized micropulsed plasma thruster (μPPT) and an advanced field emission electric propulsion (FEEP) for attitude and orbit control. They present a system consisting of four miniaturized μPPTs, installed on a single PCB. The system has a total power requirement of three and its shape is such that it fits within a standardized CubeSat.

Pugia et al. (Ref. 120) discuss a Film Evaporation MEMS Tunable Array (FEMTA), which is a thruster that employs thermally controlled microcapillaries to generate micronewton thrust with liquid ultrapure water as propellant. They present a study to demonstrate controllable single-axis rotation of a 1U CubeSat prototype with FEMTA propulsion. Preliminary testing of FEMTA has yielded thrust-to-power ratios of 230 μN/W at mass flow rates of 80 μg/s, making FEMTA a potential low-power, low-mass micropropulsion solution.

Manente et al. (Ref. 121) discuss the development of a complete and compact propulsion system based on a Mini-Helicon Plasma Thruster (mHPT) and with satellite standard data and power. The mHPT propulsion system fits in a 10- by 10- by 10-cm volume, depending on the needed propellant tank volume. The system will allow it to perform orbital variations, station-keeping maneuvers, orbit maintenance, orbit transfers, and orbit raising and decommissioning. It can potentially enable new mission scenarios as well as new deep space small-spacecraft missions.

Tsay et al. (Ref. 122) discuss the development of an iodine-fueled RF ion propulsion system that will fly on two 6U CubeSat missions as part of NASA Space Launch System (SLS) Exploration Mission—1 (EM–1) in 2019. The 70-W nominal propulsion system utilizes a 2.5-cm-grid-diameter RF ion thruster "BIT–3" and a micro-RF cathode "BRFC–1" as the neutralizer. Based on their performance validation results, a full iodine BIT–3 flight system is expected to produce 0.66- to 1.24-mN thrust and 1,400- to 2,640-s Isp, at 56 to 80 W throttleable power processing unit (PPU) input power. When given sufficient power to operate, it can provide up to 2.9 km/s velocity change (ΔV) for a 6U/14-kg CubeSat.

Stelwagen et al. (Ref. 123) discuss the development of a high-voltage stackable integrated circuit to provide a solution for the 6-kV switch and enable implementation of a PPU architecture. During the breadboard model testing, they verified that the maximum output power of a PPU with a volume of a 1/4 CubeSat cube is 20 W. At full load, the electrical efficiency of the overall PPU system is estimated to be about 80 percent. Their high-voltage switches have been verified to have a >6 kV breakdown voltage and properly conduct 1 mA of current without significant voltage drop across the drain source voltage. This technology may open the door for small CubeSats to fly new missions.

Johnson (Ref. 124) examined multiple uses of the thruster for in-space and atmospheric propulsion, as well as the creation of a CubeSat and atmospheric airship as testbeds for the thruster. The PPT was tested as a solid-propellant feed source for the high-power helicon thruster. A PPT with sulfur propellant designed for CubeSat operation, as well as the subsystems necessary for autonomous operation, was built and tested in the laboratory.

Kronhaus, Laterza, and Maor (Ref. 125) discuss a CubeSat-class micropropulsion system called the inline-screw-feeding vacuum-arc thruster (ISF–VAT). The ISF–VAT is a solid-metal propellant electric propulsion device that generates thrust by forming an arc discharge between coaxially arranged anode and cathode electrodes. They utilize an active computer-controlled feeding mechanism. Using a Ti cathode, a thrust to power ratio of 2.3 μN/W was achieved and more than 106 pulses were demonstrated. The thruster prototype dimensions are 15 by 15 by 65 mm and is ≈60 g in mass.

McTernan et al. (Ref. 126) developed a software simulation model called TeMPEST that models various storage devices such as supercapacitors, lithium-ion batteries, or a generic storage device. Their energy storage module is also capable of examining other aspects of a spacecraft's energy budget, such as the in-plane or out-of-plane contributions of the electrodynamic work done on the system. They placed an emphasis on scaling the storage devices to satisfy the requirements of the CubeSat platform.

Lappas et al. (Ref. 127) presented a concept to generate electric power for small satellites using thermoelectric generators (TEGs). Using heat sourced from the space environment, conventional thermoelectric modules connected to a dual-loop fluid system, can produce power with specific densities exceeding 20 W/kg. Experimental test results of a breadboard TEG show the feasibility of the concept and the benefits of using TEGs for long-duration, small-satellite missions.

Spangelo et al. (Refs. 128 and 129) discuss a study to establish the optimal performance parameters for future microelectric propulsion technology that are applicable to a broad range of flight demonstration platforms (e.g., dedicated 3U to 12U CubeSats to Evolved Expendable Launch Vehicle Secondary Payload Adapter- (ESPA-) class spacecraft) for a variety of applications, including LEO and Earth escape orbit transfers, travel to interplanetary destinations, hover and drag makeup missions, and performing reaction wheel-free attitude control. They developed an integrated systems-level model for propulsion, spacecraft (power, data, telecommunication, and thermal management), and orbit and attitude maneuvers to support solution space exploration.

Singh, Shrivastav, and Bhattacharya (Ref. 130) discuss the development of a high-efficiency, compact, and flexible EPS for a CubeSat. The EPS is responsible for harnessing power from solar panels, battery charging, and multidomain voltage output regulation within the CubeSat. Their work builds upon the results and learnings obtained from an EPS, which uses silicon metal-oxide-semiconductor field-effect transistors. The hardware and software aspects of the development of such photovoltaic-battery-based power management systems were examined. A dual-loop control methodology with output current control is implemented to regulate the output current when charging the battery. Their aim was to increase efficiency and have all the functionalities of its silicon counterpart in smaller dimensions.

Sanchez-Sanjuan, Gonzalez-Llorente, and Hurtado-Velasco (Ref. 131) describe the kinematic and dynamic equations to derive the CubeSat attitude. Mathematical models of solar cells and batteries are also derived to calculate the energy harvested and stored. They estimated incident average solar energy for the three scenarios indicated that the Sun pointing and free-orientation scenarios harvest more energy than the nadir-pointing one. This estimation is potentially useful in predicting the state of charge of the batteries in standby mode, allowing for determination of the time required for charging the batteries and, hence, the operating modes of the CubeSat.

Gorev et al. (Ref. 132) described a computational program developed in MATLAB® and Simulink® (The MathWorks, Inc.) that performs calculation of electric power generated by photoconverters for various missions of nanosatellites in LEO. Electric power generated by nanosatellite's solar panels was estimated for polar LEO of 450-km altitude for two versions of the satellite's static orientation. The results show how orientation maneuver at the Earth's surface point affects power generated by the satellite's solar panels.

Abdelwahab, Nawari, and Nawari (Ref. 133) aimed to study the concept of designing Sun-tracking solar panels and a maximum power point tracker for the UOKSAT–3 CubeSat, which is a 2U CubeSat with deployable solar panels. They detailed the effectiveness and importance of the tracking process, the impacts of the tracking mechanism on the attitude determination and control, and their interfacings to rotate the CubeSat. They also presented the MPPT's performance and its results to study the change of the input energy.

Wrobel et al. (Ref. 134) discuss efforts to develop the PowerCube™ (SolarWindow Technologies, Inc.), a system that integrates three novel technologies within a 1U form factor to provide enhanced power, propulsion, and pointing capabilities to enable CubeSats to accomplish high-performance missions. The PowerCube™ system combines a high-power deployable solar array, a water-electrolysis-based thruster, and a "carpal joint" gimbal to provide high-power generation, large ΔV thrust, and precision pointing. The deployable, steerable solar array provides CubeSats with 80 W of peak power and 50 W of orbit-averaged power. They present a concept design, analysis, and initial test results of the PowerCube™ components.

Salamanca, Ferro, and Paternina (Ref. 135) presented research results on multijunction solar cell technologies for space. They also present a compilation of the steps that have been followed until now in the design of a photovoltaic panel prototype according to the physical, electrical, and financial requirements in the picosatellite CubeSat Colombia 1, developed for the Universidad Distrital Francisco José de Caldas.

Oh and Park (Ref. 136) proposed to develop a concentrating photovoltaic system for CubeSats that enhances the efficiency of power generation by effectively concentrating the solar energy on the solar panels by using a multiarray lens system under the worst condition for Sun incidence angle. They conducted a feasibility study by power measurement tests using a solar simulator and a commercial multiarray lens under various light source angles.

Ali et al. (Ref. 137) describe a reconfigurable magnetorquer coil designed and implemented for the CubePMT module of a CubeSat. Their goal is to develop a CubeSat with a magnetorquer coil that has small dimensions, less weight and low heat generation inside PCB. It is integrated inside a PCB with four internal layers each with a magnetorquer coil that are treated as an individual coil and are attached through switches. Changing the arrangements of these switches, a user can use either a single coil or two, three, or four coils in series or in parallel. This reconfigurable design gives a freedom in generating any amount of dipole moment and control power dissipation and heat generation inside the CubePMT module.

Charles et al. (Ref. 138) discuss the development of miniaturized power and propellant subsystems totaling a few hundred grams in weight for a few watts. The systems have been developed for Pocket Rocket for integration within a 1U or 2U (1U = 10 by 10 by 10 cm) CubeSat. They envisioned that their miniaturized Pocket Rocket thruster could serve as a proof of concept at getting flight heritage and be a steppingstone towards the development of higher power systems since the RF power subsystem can be scaled up to a few kilowatts and drive the electrodeless neutralizer-free helicon plasma thruster.

Bennet et al. (Ref. 139) present the development of the Mini-Helicon Plasma Thruster with particular emphasis on the role of the geometric and magnetic nozzle. Testing of various configurations (plasma cavity size and shape) is carried out in the Wombat vacuum chamber equipped with a range of diagnostics (thrust balance and optical and electrostatic probes) and newly developed technologies. The results are used to develop computer simulations aiming at a better understanding of the physics and thrust generation in the nozzle.

Balan et al. (Ref. 140) present the power budget simulations performed on the satellites RO01 and RO02 in the context of the QB50 CubeSat mission. Satellites RO01 and RO02 forming the RoBiSAT space mission are part of QB50, which is the most challenging and ambitious international small-satellites collaboration. In addition to the QB50 mission objectives, RoBiSAT's goal is to test bidirectional intersatellite communication as a prerequisite for developing future formation flying missions. They investigate the concept of two identical satellites that are going to be built and operated in order to achieve these goals. A simulation was performed using the STK platform, and for a more realistic estimation, the satellite three-dimensional (3D) model has been used considering a solar cells' area, efficiency, and position. They concluded that a specific attitude requirement for the satellite has a major impact on the power generated. Starting from approximately 2-W average orbit power for a 2U CubeSat at the local time of the ascending node (LTAN) of 12 a.m., the average orbit power increases to 5.5 W for an LTAN of 6 a.m. for the same satellite. The satellite's operation phases have been computed in accord with the simulated results.

Pisal et al. (Ref. 141) describe the design and salient features of an electrical power subsystem for a repeat satellite mission. The primary objective was to raise the orbit using solar sail with scientific data collection, particularly about radiation and charge particle density over its lifetime. This mission used a battery pack capable of supporting high-current surges owing to subsequent deployments in the initial phase of the satellite after ejection from launch vehicle and because it could withstand the eclipse phase with high-load demands, attitude control system actuators, and a radiation monitoring module. Block diagram research, design techniques, and testing results were also presented.

Tsay et al. (Refs. 142 and 143) discuss developing a complete, engineering model 1U CubeSat propulsion system utilizing the nontoxic, "green" monopropellant AF–M315E. This technology demonstrator program, also known as Advanced Monopropellant Application for CubeSats (AMAC), results in a self-contained, 1.5-kg wet system that is expected to provide 0.1- to 0.5-N variable thrust and up to 565 N·s total impulse. This propulsive capability translates to a maximum of 146 m/s ΔV for a 3U, 4-kg CubeSat. The system's only input requirements are 20 W of power at the spacecraft bus voltage and an RS–422 port for communication. In addition to Busek's 0.5-N microthruster, the focal point of the AMAC technology resulted in a measured vacuum Isp of 220 s ± 5 percent at 425-mN thrust, catalyst preheat energy consumption of 1.3 Wh, bellows tank pressure proofed to 750 psig, integrated postlaunch pressure system tank demonstration, microvalve leak rate of 1.5×10^{-3} sccm gaseous nitrogen and pressure tested to 750 psig, and minimum impulse bit of 50 mN·s for the combined thruster-microvalve unit.

Conversano and Wirz (Ref. 144) discuss the feasibility of CubeSats utilizing the Miniature Xenon Ion (MiXI) thruster for lunar missions. Their investigation presents the first-order design process for developing a lunar mission CubeSat. The results from this process were then applied to a 3U CubeSat equipped with a MiXI thruster and specifically designed to reach the lunar surface from LEO. The 3-cm-diameter MiXI thruster utilized is capable of producing 0.1 to 1.553 mN of thrust with a specific impulse of over 3,000 s and is projected to be capable of generating over 7,000 m/s of ΔV for a CubeSat mission. A low-thrust trajectory model was utilized to calculate and plot Earth-Moon trajectories.

Lee et al. (Ref. 145) present a power generation model and simulation system that was developed to evaluate various objective functions describing energy management for complex satellite designs. Their model uses a spacecraft-body-fixed spherical coordinate system to analyze the complex geometry of a satellite's self-induced shadowing with computation provided by the Open Graphics Library. They optimized a CubeSat configured as a space-dart with four deployable panels. Simulation results are presented for a variety of orbit scenarios and could potentially be extended to a variety of complex satellite geometries and power generation systems.

Cordova Alarcon et al. (Ref. 146) analyzed the mission lifetime extension capability for a CubeSat smaller than 3U in a circular lunar orbit at a 100-km altitude, assuming the utilization of a state-of-the-art low-thrust electric propulsion system such as pulsed plasma thrusters with an impulse bit (Ibit) and velocity change (ΔV) below 60 μN·s and 120 m/s, respectively. Their results show the feasibility of performing various orbit correction maneuvers for the enhancement of the mission lifetime of a CubeSat, expanding the performance capabilities of CubeSats to any mission in a lunar orbit by reducing the limitation of deploying them in unstable orbits.

Pajusalu et al. (Refs. 147 and 148) describe the final design and implementation of the electrical power system for ESTCube–1, a 1U CubeSat tasked with testing the electrostatic tether concept and associated technologies for the electric solar wind sail in polar LEO. The mission required an efficient and reliable power system to be designed that could efficiently handle highly variable power requirements and protect the satellite from damage caused by malfunctions in its individual subsystems, while using only COTS components. The electrical power system was finalized in January 2013 and launched into orbit in May of 2013.

Bock and Tajmar (Refs. 149 and 150) discuss a miniaturized FEEP system called NanoFEEP. The thruster heads are compact and have a volume of less than 3 cm^3 and a weight of less than 6 g each and one thruster is able to generate continuous thrust of up to 8 μN with short-term peaks of up to 22 μN. They presented their latest performance characteristics of the NanoFEEP thrusters and miniaturized electronics.

Li et al. (Ref. 151) concentrated on the characteristics of the small size and energy shortage for standard CubeSat architectures such as the Aoxiang satellite for a centralized and modular electric power system for nanosatellites. They utilized COTS devices and discussed how to enhance antifault capabilities and operational autonomy. The validity of the designed system and engineering application value were verified through ground experiments and on-orbit data analysis of the Aoxiang-Sat.

Dahbi et al. (Ref. 152) present the design and sizing of all components of EPS such as photovoltaic solar cell specifications based on a new strategy of calculation by scenario, secondary power sources specifications presented by the batteries, and power control distribution unit. They also discuss simulation results for the management of the power system of a nanosatellite.

Ismail, Thaheer, and Yamin (Ref. 153) discuss a 1U CubeSat named MYSat. They compared the effect on power generation and the lifetime of MYSat on two conditions; first with attitude control where satellite pointing to nadir and the second is with uncontrolled attitude of the satellite. They assumed the satellite used a hexagonal solar cell with a theoretical efficiency of 29 percent identical to an Ultra Triple Junction (UTJ) solar cell (Spectrolab, Inc.). The worst-case condition, where the Earth is positioned at apogee, was chosen for the comparative study and the lifetime of the satellite is also simulated and compared.

Johnson, Carr, and Boyd (Ref. 154) discuss NASA developing a space power system using lightweight, flexible photovoltaic devices originally developed for use here on Earth to provide low-cost power for spacecraft. The Lightweight Integrated Solar Array and anTenna (LISA–T) is a launch-stowed, orbit-deployed array on which thin-film photovoltaic and antenna elements are embedded. The LISA–T has the potential to mitigate each of these limitations, especially for small spacecraft. Inherently, small satellites are limited in surface area, volume, and mass allocation; driving competition between their need for power and robust communications with the requirements of the science or engineering payload they are developed to fly. The power that can be generated by the LISA–T ranges from tens of watts to several hundred watts, at a much higher mass and stowage efficiency. In addition, UHF, S-band, and X-band antennas are being integrated into the array to move their space claim away from the spacecraft and open the door for more capable multielement antenna designs such as those needed for spherical coverage and electronically steered phase arrays.

Slongo et al. (Ref. 155) discuss a mathematically modeled energy harvesting circuit and solar panel I-V curves for different temperature and irradiance levels. The scheduling algorithm is designed to keep solar panels working close to their maximum power point by triggering tasks in the appropriate form. The scheduling algorithm was tested in FloripaSat, which is a 1U CubeSat. Test results show that the scheduling algorithm improves the CubeSat energy harvesting capability by 4.48 percent in a three-orbit experiment and up to 8.46 percent in a single orbit cycle in comparison with the CubeSat operating without the scheduling algorithm.

Uludag et al. (Ref. 156) discuss a new architecture for the electrical subsystem of a PocketQube (50 by 50 by 50 mm) in order to reduce its volume and increase the usage of empty surfaces inside the satellite. The main objective of this work is turning the EPS into a more flexible, scalable, and volume-efficient system by a physical relocation of its components and a lean approach. The EPS is scheduled to be functionally and environmentally tested in a flight representative satellite model with the aim to verify its simplification in integration, assess its true performance, as well as its reliability during launch vibration, which especially includes spring-loaded connectors.

Lee, Kim, and Shin (Ref. 157) discuss an offline design and online management of satellite power systems. They analyzed and modeled unique characteristics of a power supply and demand of a satellite, which are dictated by the periodicity of power generation from solar panels and the nonlinear behavior of rechargeable battery cells. They concentrated on cubic-shaped nanosatellites to demonstrate the effectiveness of their design and management of satellite power systems.

Alves et al. (Ref. 158) discuss the NanoSatC–Br1 CubeSat with a cubic shape with 10 cm of edges and a mass of approximately 1 kg. The primary source of electrical power of the satellite is a solar generator compound by solar cells covering the six satellite faces. In order to obtain accurate analysis of generated and consumed power, a model of the satellite was developed, and simulations were performed using electronic simulation software. They also present the

NanoSatC–Br1's electrical power subsystem and results of the electrical power model simulation, considering beginning-of-life conditions of the satellite for different load conditions and operation periods.

Ostrufka et al. (Ref. 159) present an experimental study of a TEG for electric energy generation through temperature gradients from solar panels in CubeSats. The generation capacity is analyzed for different positioning configurations of the TEG relative to each CubeSat surface. Using temperature variation profiles obtained by numerical analysis for a real CubeSat mission, they were able to determine the amount of power generated by a TEG module from the heat waste from solar panels. A comparison process between TEG and solar panel generation systems was also conducted. The proposed system can potentially generate up to 9.62 percent of the energy generated by the conventional solution, considering energy harvesting storing efficiency of 10 percent.

Bergsrud and Straub (Ref. 160) discuss a space solar microwave power transfer system (SSMPTS) that may represent a paradigm shift to how space missions in Earth orbit are designed. An SSMPTS may allow a smaller receiving surface to be utilized on the receiving craft due to the higher density power transfer (compared to direct solar flux) from an SSMPTS supplier craft. The receiving system can be efficient since it requires less mass and volume. The SSMPTS approach can potentially increase mission lifetime as antenna systems do not degrade nearly as quickly as solar panels. They presented a prospective mission feasibility using an ESPA/SmallSat-class spacecraft and a 1U CubeSat as a guide.

Piovesan et al. (Ref. 161) focused on the EPS, system responsible for generating, storing, conditioning, and supplying electrical power for the entire satellite. They presented a comparison between a conventional power converter design and an optimization design methodology for boost power converters in order to improve efficiency and to reduce volume and mass for 1U CubeSat EPS. Results have shown the method effectiveness and efficiency maximization was achieved respecting the 1U CubeSat constraints.

Orr et al. (Ref. 162) discuss the development of a modular power system (MPS) to facilitate missions with power requirements spanning two orders of magnitude. The MPS implements a battery bus with series regulators performing charge management and solar array regulation. The system consists of four primary types of units: solar array and battery regulators that can be used for solar panel isolation or current sharing with efficiencies in excess of 95 percent; switched power nodes providing programmable switched power; smart battery modules integrating batteries and charge and discharge protection, monitoring, and thermal regulation; and a power system interface backplane that connects modules and distributes power and communication. They provide a high-level overview of the MPS and how the system can be configured for missions ranging from CubeSats to kilowatt-class small spacecraft.

CubeSats and Communications

The following is an extensive review (Refs. 163 to 223) of the current CubeSat communication research and applications. As part of the CubeSat operational requirements, CubeSat operators need to comply with their country's radio license agreements and restrictions. In addition, no CubeSat can generate or transmit any signal from the time of integration into the P-POD through 45 min after on-orbit deployment from the P-POD. Communication between a remote-sensing nanosatellite and Earth significantly depends upon the efficiency of antenna systems. Body-mounted or deployable solar panels are the main source of a satellite's operating power. In addition, nanosatellite space missions are vulnerable because of antenna and solar panel deployment complexity (Ref. 164).

The essential mission requirement of a satellite is the ability to provide a link to transmit information to and from the ground station. For most CubeSat missions, data must be downlinked during short LEO ground station passes, which is a task currently performed using traditional radio systems (Ref. 203). In general, the communication system of the CubeSat is divided into two subsystems that are a telemetry and data subsystem and a beacon subsystem. The telemetry and data subsystem will ensure continuous communication with the ground station. The beacon subsystem is the main part of the communication system of the satellite that provides information about the satellite and its status in the form of continuous wave, which is encoded using Morse code. The beacon subsystem is used to locate the satellite and identify itself to other stations (Ref. 171).

Communication links between a satellite and the ground station are subject to a lot of impairments and losses such as noise and atmospheric attenuations as well as Doppler shift effects. It is quite important to design a reliable link that caters for these impairments. The main challenge is to design a communication subsystem that provides enough transmission power to close the link while being power efficient and simultaneously delivering the required link characteristics in terms of effective bit rate and bit error rate (Ref. 207).

An important consideration when planning CubeSat missions is the power budget required by the radio communication subsystem. This enables a CubeSat to exchange information with ground stations and/or other CubeSats in orbit. The power that a CubeSat can dedicate to the communication subsystem is limited by the hard constraints on the total power available due to its small size and lightweight, which limit the dimensions of the CubeSat power supply elements (Ref. 208).

Jackson, Straub, and Kerlin (Ref. 163) present and characterize an algorithm that uses chaos theory to encrypt data that can be applicable to CubeSat missions. They discuss a proof of concept of this algorithm and compare their results against Advanced Encryption Standard (AES) and Speck in terms of the speed of encryption.

Alam et al. (Ref. 164) propose a solar panel-integrated modified planner inverted F antenna (PIFA) to mitigate communication limitations due to lower UHF nanosatellite antenna designs. The proposed antenna has achieved a –10-dB impedance bandwidth of 6.0 MHz (447.5 to 453.5 MHz) with a (80- by 90- by 0.5-mm) radiating element. The antenna also achieved a maximum realized gain of 0.6 dB and a total efficiency of 67.45 percent with the nanosatellite structure and a solar panel.

Weinert et al. (Ref. 165) discuss a project sponsored by the Department of Homeland Security (DHS) Science and Technology Directorate to design and fabricate a low-power, low-weight, reliable communication solution to provide essential information. This airborne remote communication (ARC) system trades bandwidth for mobility and reliability. The ARC system is partly based on CubeSat technology and consists of the CubeSat communication technology, ground-based hardware and software components, and a platform on which the communication technology is deployed. They describe the ARC system and a demonstration highlighting the capabilities of an essential information system.

Babuscia et al. (Ref. 166) focused on telecommunication issues for interplanetary CubeSats. Interplanetary CubeSats tend to face harsher environments and longer path distances and have more navigation needs than the LEO CubeSats. They discuss the design of the telecommunication and ground support systems for two of the interplanetary CubeSat missions that will be launched on the NASA SLS EM–1: Lunar IceCube and LunaH-Map.

Babuscia et al., (Ref. 167) present a low-complexity Code Division Multiple Access (CDMA) system for CubeSats for communications between the Lunar L1 and Earth station. They used a low-density parity check (LDPC) coded CDMA with binary phase shift keying (BPSK) modulation with rectangular and half-sine pulse shaping. Except for the pseudorandom number generator seed numbers, the communication structure of all CubeSats would be identical and operating at one single RF. They present analyzed and simulated data for their proposed CDMA system.

Gunther et al. (Ref. 168) discusses establishing reliable high data rate space-to-Earth communication in the asymmetric setting of a secondary service in the 460- to 470-MHz frequency band. They present a frequency domain approach to detect and cancel narrowband interference. This approach was shown to be effective on real data collected for the Dynamic Ionosphere CubeSat Experiment mission and was developed with a view toward demonstrating a high-speed data downlink capability that may be adopted as a standard for future CubeSat missions.

Paternina-Anaya, Salamanca-Céspedes, and Ávila-Angulo (Ref. 169) describe the hardware and software necessary to implement a picosatellite network and four Earth stations. The mission of the CubeSat, Colombia 1, consists of taking electrocardiogram signals at an Earth station and sending it via picosatellite to another.

Yang et al. (Ref. 170) discuss a space optical communication and navigation system that provides high data rate communication, precise measurements of spacecraft ranging, range rate, and accurate spacecraft pointing. A complete breadboard system was built and includes both space and ground terminals. Along with a 622-Mbps data link, two-way ranging was conducted. Accuracies of 23-μm ranging and 23-μm/s range rate were achieved in 1-s integrating time. The ranging and range rate accuracies were achieved through the relative phase measurement of transmit and receive clocks with Dual Mixer Timer Difference measurement apparatus.

Humad, TagElsir, and Daffalla (Ref. 171) discuss ISRASAT1, which is a nanosatellite designed, built, and integrated at the Institute of Space Research and Aerospace (ISRA). The beacon subsystem is separated from telemetry and data transmitter and will operate in the VHF band at 128 MHz. For the telemetry and data subsystem, the data radio transceiver in UHF band at 868 MHz will be used. They presented the hardware and software design and implementation of the communication subsystem of the ISRASAT1 CubeSat.

Vertat et al. (Ref. 172) discuss the development and evaluation of a simple method for received signal quality for CubeSats. This method was applied on several received signals from picosatellites and the results are discussed. They also discuss the practical side of picosatellite signal receiving and statistics of a picosatellite passing above a ground station.

Tresvig and Lindem (Ref. 173) discuss the design of a communication system for a nanosatellite space weather mission and how the increased capabilities of integrated circuits have reduced the complexity and size of the satellite subsystems.

Ceylan et al. (Ref. 174) discuss a low-cost S-band communication system design for nanosatellite structures. They designed a 2.4-GHz (S-band) communication system for LEO satellites (700 to 900 km). Their system includes system-on-chip transmitter device, preamplifier, band pass filter, power amplifier, and microstrip antenna array. They realized output power of the system at 35 dBm for 2.4 kBd data rate.

Arruego et al. (Ref. 175) discuss an Optical Wireless Links for intra-Spacecraft communications (OWLS) technology. OWLS has been recently applied to the On-Board Data Handling subsystem of OPTOS satellite, the first fully wireless satellite. They address the communication challenges between a sensor and a meteorological station on the Martian surface, within the Mars MetNet Precursor Mission.

D'Humières et al. (Ref. 176) present the advanced Concept for laser uplink/downlink CommuniCation with sPace Objects (C3PO) system, and the initial results of the development of its key technologies. They targeted the design of a communication system that uses a ground-based laser to illuminate a satellite and a modulating retro-reflector to return a beam of light modulated by data to the ground. The C3PO project aims to achieve data rates of 1 Gbps between LEO satellites and Earth with a communication payload mass of less than 1 kg.

Aragõn et al. (Ref. 177) present a communication for OPTOS that incorporates a customized subsystem that is being thoroughly tested and will try to ensure the quality of the radio link. Their subsystem operates in the frequency of 402 MHz and consists of a transceiver and four monopoles onboard the satellite and a directional antenna together with diverse and reliable ground equipment. They also detail the telemetry, tracking, and command; ground station equipment; and antennas.

Clements et al. (Ref. 178) discuss the nanosatellite optical downlink experiment (NODE), which implements a free-space optical communications capability on a CubeSat platform that can support LEO to ground downlink rates of 10 Mbps. A primary goal of NODE is to leverage commercially available technologies to provide a scalable and cost-effective alternative to RF-based communications. The NODE transmitter uses a 200-mW, 1,550-nm master-oscillator power-amplifier design using power-efficient M-ary pulse position modulation. They capture trades and technology development needs and outline plans for integrated system ground testing.

Hunyadi et al. (Ref. 179) present the MEROPE (Montana EaRth-Orbiting Pico-Explorer) communications subsystem that consists almost entirely of COTS components. MEROPE uses the AX.25 packet radio protocol at 1,200 Bd. Uplink is at a frequency of 145.835 MHz with 20 kHz of available bandwidth. Downlink is at 437.445 MHz with a 30-kHz bandwidth. The MEROPE antenna is a center-fed dipole tuned to the 2-m uplink, which is nearly harmonic with the 70-cm downlink.

Carrasco-Casado et al. (Ref. 180) present the main points and conclusions from the Keck Institute for Space Studies (KISS) workshops. The KISS group consisted of a group of space scientists and laser communications (lasercom) engineers brought together to address the current challenges that CubeSat optical communication technology faces. After two 1-week workshops, the working group addressed three study cases: LEO, crosslinks, and deep space.

Lim et al. (Ref. 181) describe an optical communications system payload development for a CubeSat-based satellite crosslink, operating at a 1-km range. They designed and assembled an engineering model that will serve as a prototype to conduct performance testing and to extract key payload requirements such as volume, weight, power, and pointing accuracy for signal acquisition and tracking and follow-on design stages beyond an engineering model. This prototype consists of two main optical subsystems: a receiver system to detect and track incoming signals and a transmitter system to broadcast towards a sister satellite. This design is referred to as the "bistatic design", requiring an identical transmitter and receiver pair for two-way laser communication.

Rajguru et al. (Ref. 182) discusses the reduction of generic RF communications system mass and size by replacing it with lasercom technology, which can fit into a 6U CubeSat constraint. Achieving this miniaturization can lower the cost of deep space missions, thereby making it more accessible to small-budget organizations such as university research labs.

Babuscia et al. (Ref. 183) propose to develop a communications system for CubeSats in formation that operate in the vicinity of the Moon using a CDMA system. They investigated Doppler effects on CDMA communications systems such as the effects of Doppler shift and rate on the CDMA system performance as a result of the CubeSat constellation orbiting in a halo orbit around Earth-Moon Lagrange Point L1. They present a detailed analysis and simulation of the system in the presence of Doppler frequency and an unknown carrier phase.

Tubbal, Raad, and Chin (Ref. 184) propose the use of a wideband S-band F-shaped patch antenna for CubeSat communications to broaden bandwidth. They utilized two arms with different lengths to generate a second resonant frequency. They studied the effect of the arm length and width on the return loss, resonant frequency, and impedance bandwidth on a 3U CubeSat. Their simulation results show that the antenna achieves a wideband of 1,121 MHz (1.606 to 2.727 GHz) with a return loss below –10 dB over the entire frequency band from 1.606 to 2.727 GHz. The antenna has a high gain of 8.51 dB and a small return loss of –32.85 dB at 2.45 GHz.

Palo (Ref. 185) provides an overview of current CubeSat communications systems capabilities in addition to details about an effort to develop a high-rate CubeSat communications system that is compatible with the NASA Near Earth Network (NEN). The system includes a 200 kbps S-band receiver and a 12.5 Mbps X-band transmitter.

Neumann et al. (Ref. 186) demonstrate the feasibility of establishing a Q.Com uplink with a 3U CubeSat using COTS that primarily have a space heritage. They discuss how to leverage the latest advancements in nanosatellite body pointing to show that a 4-kg CubeSat can generate a quantum-secure key. The also performed a comprehensive link budget and simulation to calculate the secure key rates. They discuss design choices and tradeoffs to maximize the key rate while minimizing the cost and development needed for global scale Q.Com.

Babuscia et al. (Ref. 187) discuss the review and possibility of combining two solutions for the problem: the use of inflatable antenna reflectors and the arrays across multiple spacecraft. They presented an overview of cooperative communications techniques across small platforms and the main challenges of arraying antennas on different spacecraft are underlined. They combined the two solutions to provide a first-order quantification of the advantages in terms of effective isotropic radiated power and data rate and range.

Kim and Moon (Ref. 188) present a radiofrequency distribution unit (RFDU) conceptual design for Korea Pathfinder Lunar Orbiter (KPLO) communications relay. They discuss the KPLO RFDU and the RF path multiplexing conceptual design that results in the same band.

Babuscia, Divsalar, and Cheung (Ref. 189) propose a communications system for CubeSats in formation to operate in the vicinity of the Lunar Lagrangian L1. They considered an improved low-complexity CDMA system for CubeSats for communications between the Lunar L1 and Earth station. They analyzed and simulated the proposed improved CDMA system for a concept constellation of CubeSats.

Babuscia et al. (Ref. 190) propose cooperative communications approaches in which multiple CubeSats communicate cooperatively together to improve the link performance with respect to the case of a single satellite transmitting. Three approaches were proposed: a beam-forming approach, a coding approach, and a network approach. The approaches are applied to the specific case of the Solar Observing Low frequency Array for Radio Astronomy/ Separated Antennas Reconfigurable Array (SOLARA/SARA) concept: a proposed constellation of CubeSats at the Lunar Lagrangian point L1 that aim to perform radio astronomy at very low frequencies (30 kHz to 3 MHz). They describe the development of the approaches, the simulation, and a graphical user interface that can be applicable to multiple constellation configurations.

Su, Lin, and Ha (Ref. 191) investigate the feasibility of deploying CubeSat constellations with intersatellite links for the delivery of global continuous communication. The proposed and verified CubeSat constellation designs are for various mission scenarios using a simulation toolkit commonly used by space engineers.

Chaabane, Jaballah, and Rokbani (Ref. 192) present an antenna devoted to CubeSat communications systems based on a Flower Pollination Algorithm (FPA) for the antenna angular inset-feed and its depth as well as the antenna radius. Their FPA metaheuristic is used to optimize the performance of each circular patch in terms of return loss, gain, and impedance. They obtained a return loss near the Industrial, Scientific, and Medical (ISM) frequency of 2.45 GHz at –27.9663 dB and the simulated gain reached 9.06 dB.

Schaire et al. (Ref. 193) discuss NASA scientists and engineers across many of the NASA Mission Directorates and Centers developing exciting CubeSat concepts and welcome potential partnerships for CubeSat endeavors. The NASA Space Communications and Navigation (SCaN) Program’s NEN and Space Network (SN) are customer-driven organizations that provide comprehensive communications services for space assets including data transport between a mission’s orbiting satellite and its mission operations center. This report presents how well the SCaN networks, SN and NEN, are currently positioned to support the emerging small-satellite and CubeSat market as well as planned enhancements for future support.

Oi et al. (Ref. 194) discuss quantum communication as a prime space technology application for CubeSats that can potentially offer near-term possibilities for long-distance quantum key distribution (QKD) and experimental tests of quantum entanglement. They outlined a recent proposal to perform orbit-to-ground transmission of entanglement and QKD using a CubeSat platform deployed from the ISS. The CubeSat Quantum Communications Mission (CQuCoM) would be a pathfinder for advanced nanosatellite payloads and operations and could potentially establish the basis for a constellation of LEO-trusted nodes for QKD service provision.

Khac et al. (Ref. 195) proposed a circular polarization array antenna for CubeSat satellite applications in X-band ranging from 8.0 to 8.4 GHz. They introduced a sequential-phased rotation principle combined with an equal power divider for a 4- by 4-array antenna as well as a dual-feed technique to generate circular polarization for a single antenna element that has the same magnitude and 90° phase deviation between two input ports. They achieved X-band bandwidth coverage ranging from 8.0 to 8.4 GHz completely while the axial ratio is less than 3 dB and the total gain of 15.89 dBi was achieved at 8.2 GHz.

Santangelo and Skentzos (Ref. 196) discuss flight testing and certifying the QuickSAT/Vehicle Management System (VMS), the prototype of the FRNCS–P high-speed flight computer and the LinkStar global communications radio on the Boeing RADSat. The RADSat is a 2U CubeSat that will be deployed from the ISS via the Nanoracks Program. They aimed to test and demonstrate full duplex communications between the satellite and ground via the Globalstar satellite network utilizing the LinkStar radio architecture. Globalstar is a constellation of 32 satellites in LEO providing global data and voice services for a range of uses including oil rigs, shipping containers, gas pipelines, and supporting remote communications. Their research focused on adapting the Globalstar GSP–1720 modem and creating the LinkStar radio architecture for use in space. Their models show LinkStar can provide up to 60-percent continuous coverage, both data download and upload through a secure internet link. For the LinkStar–STX3, over 95-percent downlink coverage can be provided. In both radio systems, the data itself is further encrypted to ensure the information transmitted to and from a satellite is secure.

Kingsbury et al. (Ref. 197) describe the design of a compact free-space optical communications module for use on a nanosatellite. They present results from a detailed trade study to select an optical fine-steering mechanism compatible with our stringent size, weight, and power (SWaP) constraints. Their overall goal is to develop a lasercom payload that fits within the SWaP constraints of a typical 3U CubeSat. They presented an analysis of the device's transfer function characteristics and ways of predicting this behavior that are suitable for use in the control processor.

Konte, Trafford, and Schmalzel (Ref. 198) discuss the development of an extensible electronic data sheet to extend the power of the transducer electronic data sheet concept that can be applicable to CubeSat communications protocols, which are based on IEEE 1451.4. Standards.

Rana et al. (Ref. 199) discuss the mission of Space Concordia's ground station establishing communication with its main 3U CubeSat, Aleksandr. Space Concordia has utilized Open MCT, a mission control software developed by NASA and based on a web framework that ground station operators can tailor to process and visualize mission-specific telemetry. They have created several libraries under open source licenses to facilitate the use of Open MCT by other ground stations.

Khotso, Lehmensiek, and Van Zyl (Ref. 200) investigated the effect of the antenna pattern on the communication time between a ground station and a LEO satellite with passive attitude control. Two low-profile antennas that fit on a 3U CubeSat were considered, more specifically, a high-gain patch and a low-gain monopole-like patch antenna. The communications system investigated was for high-speed S-band communication.

Zaman et al. (Ref. 201) describe the design tradeoff between the field of view (FOV) and collection efficiency in receiver designs using COTS optics and detectors. They also discuss the design tradeoffs in transmitter design for optimum performance. They surmised that in order to achieve maximum signal-to-noise ratio at long distance (≥100 km), the laser beam diameter needs to be 80 to 90 percent of the scanning mirror diameter. In addition, they show that the intrinsic FOV of high-speed (≥600 MHz) Avalanche Photodiodes (APD) can be increased to ≥3° by incorporating optimized optics considering form factor of the CubeSat system. They presented a scalable detector array design method using COTS components to achieve a wide full FOV (≥12°) with a uniform collection efficiency around 30 to 60 percent. They demonstrated a multiwavelength full duplex communications system based on dichroic filters as the duplexer that shows significantly low crosstalk.

Vourch and Drysdale (Ref. 202) presented a study of a simple communications scenario between two CubeSats using a V-band "Bull's eye" antenna specifically designed for this purpose. The return loss of the antenna has a –10 dB bandwidth of 0.7 GHz and a gain of 15.4 dBi at 60 GHz. The communications scenario study shows that using 0.01 W VubiQ modules (Vubiq Networks, Inc.) and V-band Bull's eye antennas, CubeSats can efficiently transmit data within a 500-MHz bandwidth and with a 10^{-6} bit error rate while being separated by up to 98 m, under ideal conditions, or 50 m under worst-case operating conditions (5° pointing misalignment in E- and H-plane of the antenna, and 5° polarization misalignment).

Nguyen et al. (Ref. 203) present the NODE design, capable of providing a typical 3U (30 by 10 by 10 cm) CubeSat with a comparatively high data rate downlink. The NODE optical communications module was designed to fit within a 5- by 10- by 10-cm volume, weigh less than 1 kg, and consume no more than 10 W of power during active communications periods. Their design incorporates a fine-steering mechanism and beacon-tracking system to achieve a 10-Mbps link rate. They describe the system-level requirements and designs for key components, including a transmitter, a beacon-tracking camera, and a fast-steering mirror. They also present simulation results of the uplink beacon tracking and fine steering of the downlink beam, including the effects of atmospheric fading and on-orbit environmental disturbances to demonstrate the feasibility of this approach.

Chalermwisutkul et al. (Ref. 204) discuss the development of a 1U CubeSat (KNACKSAT) communication system utilizing Gaussian minimum shift keying- (GMSK-) modulated data from the satellite that is transmitted to the ground station via a UHF channel. The uplink of the frequency shift keying- (FSK-) modulated command from ground to the satellite is carried out via a VHF channel. Half wavelength dipoles for the transmit and receive antennas aboard the KNACKSAT CubeSat were chosen. The developed communication system has been successfully tested with data communication between the satellite and the ground station.

Challa and McNair (Ref. 205) investigate how power, volume, and geometry constraints of a CubeSat cripple CubeSat communications and introduce CubeSat Torrent, a Torrent-like distributed communications system, for CubeSat clusters. CubeSat Torrent aims to increase the downlink and uplink speeds of large files by distributing pieces of the files to CubeSats in the cluster and downloading different pieces of the files simultaneously from different CubeSats. The proposed system proved, through simulation experiments, to substantially improve the download and upload times of large files by a factor of about the size of the cluster.

Akyildiz, Jornet, and Nie (Ref. 206) discuss a CubeSat design with reconfigurable multiband radios for communication in dynamic frequencies. Their multiband radio design is realized by two complementary approaches: an electronics-based and a photonics-based approach. Their multiband communication covers a wide range from radiofrequencies (2 to 30 GHz), millimeter wave (30 to 300 GHz), terahertz band (up to 10 THz), and optical frequencies (with typical bands of 850 nm/350 THz, 1,300 nm/230 THz, and 1,550 nm/193 THz). Key parameters in the satellite constellation design are investigated to explore the feasibility of deployment at different altitudes in the exosphere orbit (500 km and above).

Latachi et al. (Ref. 207) present a link budget analysis for communication between a nanosatellite orbiting at LEO and a low-cost mission-control ground station. The analysis employs relevant deterministic, empirical, and statistical models as prediction tools, to make pertinent choices for both the flight nanosatellite compliant communications board and the ground station hardware and link protocols.

Popescu (Ref. 208) presents a detailed power budget analysis that includes communications with ground stations as well as with other CubeSats. For ground station communications, they outline how the orbital parameters of the CubeSat trajectory determine the distance of the ground station link and present power budgets for both uplink and downlink that include achievable data rates and link margins. For intersatellite communications, they studied how the slant range determines power requirements and affects the achievable data rates and link margins.

Neumann et al. (Ref. 209) present a feasibility study for a fully functional 3U-CubeSat-based quantum receiver. They provide a complete link loss analysis, count rate estimations, and preliminary design. They also discuss solutions to key problems such as satellite pointing errors and measurement and detection issues. Using current technology, they show that the CubeSat is feasible and can be used to violate a Bell-like inequality over a free-space distance of 500 km.

Arvizu et al. (Ref. 210) present a prototype of an acquisition, tracking, and pointing (ATP) system intended to be used in an optical quantum communications link between a CubeSat and an optical Earth station. The ATP system is designed in such a way that alignment on the satellite with respect to the optical Earth station will be carried out based on the concept of an artificial star with the help of an astronomical 14-in. Cassegrain telescope. They also present characterization results of ATP performance under controlled conditions of optical turbulence in the laboratory and in shorthand medium-distance terrestrial links.

Rodriguez-Osorio and Ramírez (Ref. 211) present a hands-on education project the aim of which is the specification, design, building, and measurement of an antenna for communications between nanosatellites. The project lies within the framework of School of Telecommunications Engineering (ETSIT) Technical University of Madrid (UPM) innovative educational activities in the area of space technology, where students play a leading role in real engineering projects.

Bulanov et al. (Ref. 212) evaluated intersatellite communications for a LEO CubeSat network using determination and estimation of quality of service (QoS) parameters and evaluation of the feasibility of a massive multiple input, multiple output (MIMO) system link. They investigated the QoS parameters for an intersatellite link and factors affecting it and a theoretical design with a constructive drawing of massive MIMO. The possibility and time duration of intersatellite communication were calculated for three different cases using real data and including massive MIMO. Based on simulation results, suggestions and possible technical and nontechnical solutions were highlighted together with future studies and simulations.

Peng et al. (Ref. 213) presented a BPSK modulation scheme using dual gain-switched diode lasers that was developed and demonstrated within an end-to-end link testbed to achieve signal acquisition under extremely poor signal-to-noise conditions (–43.5 dB average signal-to-noise power ratio at a 1-MHz symbol rate) to simulate direct-to-Earth links, while simultaneously targeting a limited SWaP footprint (1.5U envelope). They discussed additional system design and constraints for the compact laser transmitter.

do Nascimento et al. (Ref. 214) conducted an experiment comparing different transceivers for both satellites and ground station in order to guarantee the fastest and cheapest data transmission for the mission. They also calculated the data volume that will be sent during the entire mission in order to determine which communication equipment will maximize this mission’s efficiency.

Clark et al. (Ref. 215) describe the characteristics and control of a new CubeSat transceiver. The new transceiver provides an estimated 300-percent increase in data throughput for a typical 45° maximum elevation angle LEO pass over the Aerocube–2 transceiver.

Popescu, Harris, and Popescu, (Ref. 216) examine operational constraints for CubeSats placed in LEOs and how they impact the design of their communications subsystem.

Perea-Tamayo et al. (Ref. 217) proposed a LEO relay constellation formed by a ring of nanosatellites utilizing S-band for data relay and UHF, VHF, and S-band for user communication. The proposed constellation can be established at low cost and can significantly increase the available communication time of near-polar-orbit satellites, drastically increasing the available communications budget. A nine relay-satellite-based relay belt can increase link availability for a satellite in near-polar orbit by up to 945 percent.

Muri and McNair (Ref. 218) present a survey detailing past and planned large intersatellite linking systems. They also chronicle CubeSat communications subsystems used historically and in the near future. In addition, they examine the history of internetworking protocols in space and open research issues with the goal of moving towards the next-generation intersatellite-linking constellation supported by CubeSat platform satellites.

Kara et al. (Ref. 219) discuss a research group that concentrated on (1) short- and long-term technical challenges, (2) policy requirements, (3) radio communication bandwidth limitations, (4) data collection and transmission regulations, and (5) the standardization of the CubeSat communications system. The group suggests a CubeSat network system architecture including interswarm and intraswarm constellations, optical and laser communications, and delay-tolerant networks. The proposed CubeSat communications network also consists of interswarm constellation communications along with intraswarm constellations sustained through four different basic data links, a mother-daughter satellite framework, and net-neutrality throughout the network. The group's overall goal is to help all users and operators in the CubeSat sector, including entrepreneurs, licensing bodies, and end users. Saving time for everyone while achieving maximum efficiency and utilization of the time.

Polly et al. (Ref. 220) conducted a trade study to decide which optical configuration is best for a CubeSat laser communication payload, bistatic or monostatic. The bistatic configuration used two parallel lasers (one each for uplink and downlink). The monostatic configuration used two collinear lasers. Proof-of-concept short-range laser communication systems were built and tested to measure performance. Measures of effectiveness were weighted by a pairwise comparison and the monostatic and bistatic systems were compared in a house of qualities. The monostatic system design was deemed to be the better optical configuration.

Corpino and Stesina (Ref. 221) detail a communication anomaly that occurred on the CubeSat mission E–st@r–II, which was launched in April of 2016. This report describes the investigation of a major anomaly that seriously affected mission operations, that is, low signal-to-noise ratio of downlink communication. No signal could be received at the main control station. Only ground stations with high-gain antennas and/or proper system setup could receive and decode E–st@r–II packets. Both space and ground segments were identified to be part of the problem. A potential defect was detected on the coaxial cable connection to the antenna, which might have caused the final mishap under investigation. The analysis also showed that an effective ground segment helps mitigate the impact of the anomaly and it may be worth investing more on this mission element.

Muri, Challa, and McNair (Ref. 222) investigated CubeSat communications for a 2.45-GHz bandwidth rather than the typical MHz frequency. This higher frequency provides the bandwidth needed for increasing the data rate. A deployable hemispherical helical antenna prototype was built and transmission between two prototype antenna equipped transceivers at varying distances tested the helical performance. When comparing the prototype antenna's maximum transmission distance to the other commercial antennas, the prototype outperformed all commercial antennas, except the patch antenna, which was due to the helical antenna's narrow beam width. This can lead to communications advancements by implementing a more accurate alignment with the satellite's directional antenna to downlink with a terrestrial ground station.

Moll et al. (Ref. 223) describe the concept and hardware of three generations of Optical High Speed Infrared Link System (OSIRIS) laser communication terminals for LEO satellites. The first type applies laser beam pointing solely based on classical satellite control, the second uses an optical feedback to the satellite bus, and the third comprises a special course pointing assembly to control beam direction independent of satellite orientation. Two ground stations will be available for future testing, an advanced stationary ground station and a transportable ground station.

Summary and Conclusions

As mentioned in the Executive Summary, a CubeSat is an evolving and emerging technology that gives a novice or advanced researcher relatively affordable access to space research experiments and applications. The initial CubeSat standard was created in 1999 by California Polytechnic State University, San Luis Obispo and Stanford University's Space Systems Development Laboratory to facilitate direct access to space for university students. This initial CubeSat standard has now been adopted by hundreds of organizations worldwide and includes not only universities and educational institutions, but private firms and government organizations. Dozens of CubeSats have been launched since 2003 and have come from more than 29 states in the United States. The CubeSat standard facilitates frequent and affordable access to space with launch opportunities available on most launch vehicles.

CubeSats are a class of research spacecraft called nanosatellites and are built to standard CubeSat Units or U dimensions of 10 by 10 by 10 cm and are formally classified as 1U, 2U, 3U, or 6U in size. Most CubeSats are deployed from a Poly-Picosatellite Orbital Deployer called a P-POD. Partnerships among NASA, U.S. industry, and educational institutions are being formed to build upon existing successful CubeSat initiatives with a goal to expand and include launching 50 small satellites from 50 states within the next several years.

An extensive and detailed literature review that included over 835 citations was conducted to provide a comprehensive resource on both NASA and non-NASA CubeSat experiments and applications that can serve as a guide for background information on CubeSats as well as a valuable resource of "lessons-learned" from CubeSats that have been launched in the past.

While we choose to concentrate on four areas (thermal management, deployment mechanisms, power generation, and communications) that covered over 220 citations, there are many other areas that are essential to increasing the probability of success for a CubeSat launch. To that end, we have included over 600 additional citations in the bibliography to serve as a reference guide to anyone interested in CubeSat technology, from the middle-school student up to the engineering professional. The overall goal was to provide a CubeSat research hub proving past and present research into CubeSat planning, development, implementation, and experimentation as well as prelaunch, during launch, and postlaunch.

Lastly, one of the big drivers to future CubeSat missions is maximizing the utilization of the limited power available while pushing the performance of its capabilities. Finding the capacity to increase the efficiency and computing ability of CubeSat processing elements while providing improved power performance will be a major focus of next-generation CubeSat missions. Current technologies are emerging that use deep learning and cognition to improve the performance. Neomorphic hardware delivers computing at orders of magnitude gains all while providing speed, intelligence, and better functionality. This can go a long way to having CubeSat missions that maximize power usage by utilizing brainlike intelligence when handling CubeSat operations.

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