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Review Article

Towards the Thousandth CubeSat: A Statistical Overview

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CubeSats have become an interesting innovation in the space sector. Such platforms are being used for several space applications, such as education, Earth remote sensing, science, and defense. As of May 31st, 2018, 855 CubeSats had been launched. Remote sensing application is the main sector in which CubeSats are being used, corresponding to about 45% of all applications. This fact indicates the commercial potential of such a platform. Fifty eight countries have already been involved with developing CubeSats. The most used CubeSat configuration is 3U (about 64%), followed by 1U (18%), while 6U platforms account for about 4%. In this paper, we present an analysis of the current situation regarding CubeSats worldwide, through the use of a dataset built to encompass information about these satellites. The overall success rate of the CubeSat missions is increasing over time. Moreover, considering CubeSat missions as a Bernoulli experiment, and excluding launch failures, the current success rate was estimated, as a parameter of a binomial distribution, to be about 75%. By using a logistic model and considering that the launchings keep following the current tendency, one can expect that one thousand CubeSats will be launched in 2021, within 95% certainty.

1. Introduction

The term CubeSat is used to describe a small satellite whose basic unit form is a 10 cm edge cube, namely 1U. CubeSat units can be put together to form bigger artifacts, like 2U, 3U, 6U, and so forth. CubeSats must follow the standards defined by the CubeSat Design Specification [1–5], which includes compliance with flight safety guidelines.

The motivation for the initial development of CubeSats was educational [6, 7]. The idea was to provide hands-on experience to students in space activities, allowing them to work on the entire cycle of a space project, from the initial concept until its operation in space. Due to this motivation, it was mandatory that development, launching, and operation costs were kept to the lowest possible figures, which led, among others, to project standardization (e.g., [8–10]). In order to achieve the aimed project cost reduction, the use of commercial off-the-shelf (COTS) components was encouraged along with the reduction of the number of tests. As a consequence, large development teams were no longer necessary, which helped in shrinking even more the costs of CubeSat missions. Depending on which application a CubeSat mission is designed for, its cost can range from a few tens of thousands to a few million USD, with development time spanning from about one year to a couple of years.

When the first CubeSats were launched in the early 2000s, there was a general perception that they were just toy satellites designed to fulfil the needs of student training or to meet some amateur demands. Later, it was understood that CubeSats could also be used for other applications, such as testing of technologies and science missions [11], like those related to astronomy [12–14] and space weather [15].

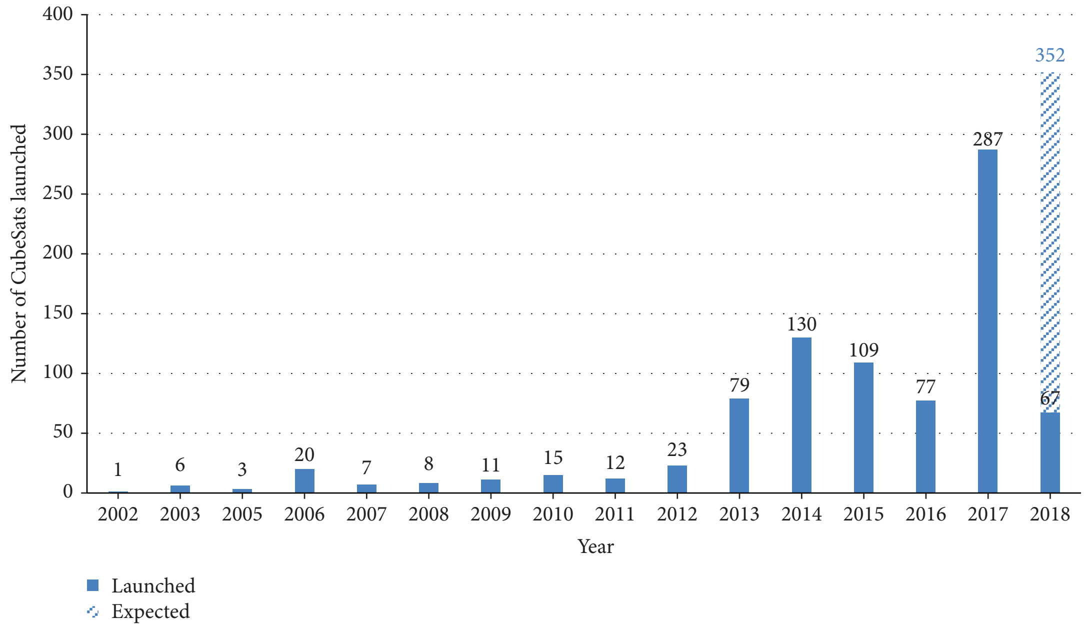

Figure 1: Number of CubeSats launched per year from 2002 to May 31, 2018, totaling 855 artifacts.

In September 2012, the hundredth CubeSat was launched. A review on the first one hundred CubeSats can be found in Swartwout [16].

CubeSats are being considered as a competitive solution for space applications as they allow equilibrium among crucial variables of a space project, such as development time, cost, reliability, mission lifetime, and replacement. The tolerance in risk acceptance for CubeSat missions is more flexible than traditional satellite development methodology. ISO 19683:2017(E) addresses this methodology. CubeSats also represent a trend in miniaturization of space artifacts and their associated technologies (e.g., [17–19]).

Besides being such a disruptive technology regarding satellite development, CubeSats are changing the way satellites are been launched into space. Contrariwise to the traditional satellite launching logic, in which one or just a few satellites are launched by a single vehicle, the intense use of the International Space Station (ISS) and the great number of satellites launched by a single vehicle are among the innovations presented by such small satellites. For instance, in 2013, 84 CubeSats were launched from ISS; in 2014, 37 CubeSats were launched by Dnper; and, in 2016, a record of satellites launched by a single rocket was established by PSLV, with 101 CubeSats launched at once along with 3 other satellites.

These facts called the attention of private companies and government institutions worldwide, which envisioned an opportunity of implementing space missions that would not be possible to implement through traditional satellite development methodology due to the high costs associated to such methodology.

In view of the above facts, it is interesting to examine the current global situation regarding CubeSats, such as the number of launchings, which is getting close to one thousand, applications they are devoted to, number of technical and scientific papers, and patents. An overview of these figures allows an analysis of the role of CubeSats in the space sector worldwide. This paper is a contribution towards this goal, as it presents a statistical overview of the information related to all 855 CubeSats launched up to May 31, 2018. This paper is divided into five sections: the introduction above; a second section describing a CubeSat database developed by the Center for Strategic Studies and Management (CGEE) (Centro de Gestão e Estudos Estratégicos, in Portuguese); a third section, where several data regarding CubeSats are presented, including the number of launched satellites, their respective applications, amount of technical and scientific productions, such as papers and patents, and some considerations regarding CubeSat launchers; a fourth section, where a forecast based on a logistic model is presented, showing the expected growth in the number of CubeSat launchings; and the fifth section presenting the final remarks.

2. The CGEE CubeSat Database

CGEE maintains a dataset on CubeSats with information regarding these artifacts. CGEE's interest on CubeSats began a few years ago when a routine activity to monitor potential innovations in the space sector, known as Observatório de Tecnologias Espaciais—OTE (Portuguese for Space Technology Observatory), detected an overall increase of the use of small-sized satellites to address several demands for space applications. In particular, within this satellite category, CubeSats presented an interesting potential to truly become a space innovation, due to their low development costs and broad applicability. In order to follow this innovation, it was decided to create a database with relevant information regarding CubeSats. This dataset was designed bearing in mind the intention of extending existing datasets

Number of launched CubeSats

Country	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total of CubeSats
Kazakhstan													1		1
Chile													1		1
Costa Rica														1	1
Colombia			1												1
United Arab Emirates													1		1
Slovakia													1		1
Hungary								1							1
Pakistan									1						1
Poland								1							1
Czech Republic													1		1
Romania								1							1
Uruguay										1					1
Estonia									1						1
Kenya														1	1
Vietnam								1	1						2
Bulgaria														1	1
Iraq										1					1
Puerto Rico													1		1
Austria				1									2		3
Ecuador									2						2
Lithuania										1			1		2
Argentina									2						2
Finland													2		2
Greece													2		2
Ukraine										1			1		2
Switzerland					1	1							1		3
South Africa									1				2		3
Brazil										1	2				3
Norway	1	1							1						3
Peru									1	2					3
Sweden													3		3
Holland				1					2						3
Belgium										2		1			3
Canada				1								1	1	1	4
Australia													4		4
France								1					2	1	4
India						1	1					2			4
Israel										1			3		4
Turkey					1				1				2	1	5
Spain								1	2			1	1		5
Singapore									1	2	2				5
Italy								2				2	1		5
United Kingdom									2	1	1		2	2	8
Denmark				1					2	1	2	1		2	9
Russia										2		2	6		10
South Korea		1							3				3	6	13
Germany	1				2				5			1	2	1	12
Japan	1	3		1	1	2		3		3	1	5		1	21
China										1	4	2	8	7	22
United States		15	6	3	6	11	11	12	51	110	97	57	222	42	643
Total	3	20	7	8	11	15	12	23	79	130	109	75	277	67	836

Launching year

Figure 2: Number of CubeSats launched per year per country from 2005 to May 31, 2018.

(e.g., [16, 20, 21]). It contains information about all CubeSats launched so far. The data presented in this paper cover information updated up to May 31, 2018. This dataset is available at https://www.cgee.org.br/web/observatorio-espacial/bancos-de-dados.

The CubeSat database contains information such as mission objective, launch date, contractor, CubeSat class (1U, 2U…), launch vehicle, functional mission status, payload description, platform capabilities, command and data handling, orbit information, ground stations used, and references to the missions. As of May 31, 2018, data on 855 CubeSats are available at the CGEE database.

3. CubeSats by the Numbers

In subsections 3.1 to 3.9, we present a statistical overview of the general information regarding CubeSats.

3.1. Number of CubeSat Launchings. In Figure 1, the number of CubeSats launched per year from 2002 is shown, starting from the launched of MEPSI, the first CubeSat-like picosatellite, up to May 31, 2018, totaling 855 artifacts.

The drop in the number of CubeSat launchings observed in the years 2015 and 2016 was due to launcher failure which held off many scheduled launches. Some of them were

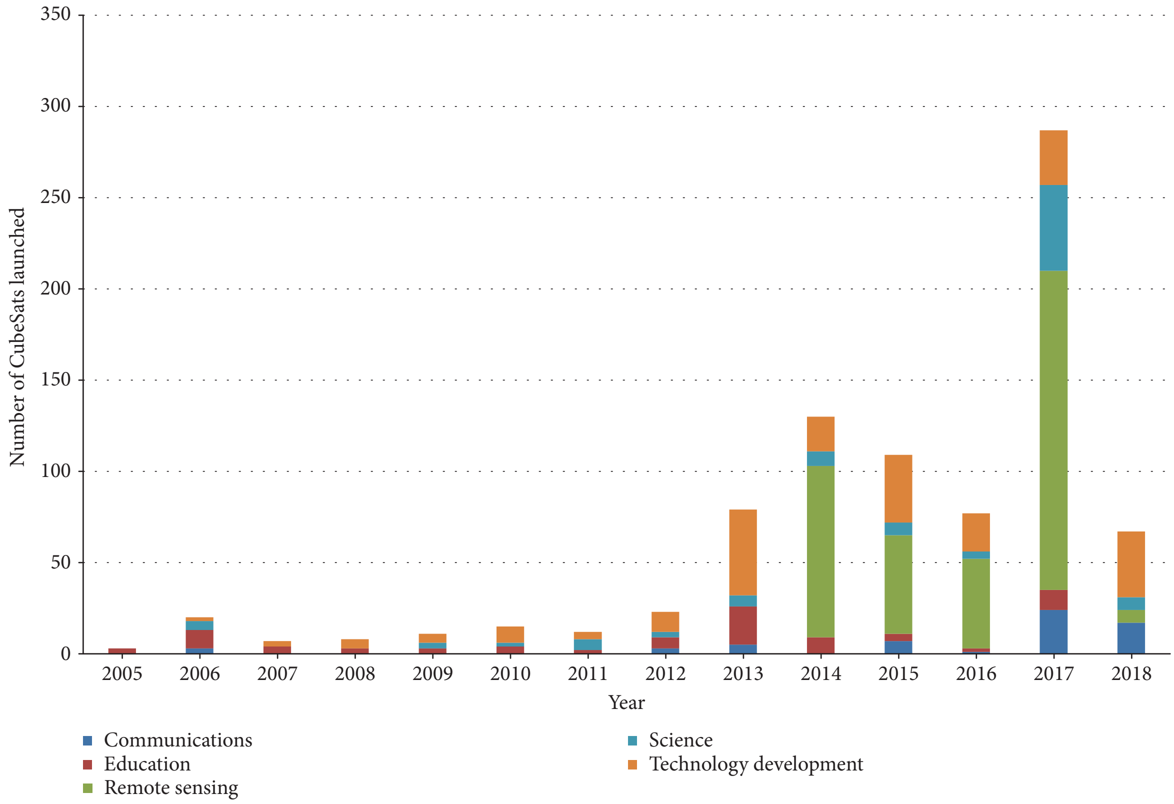

FIGURE 3: CubeSats launched per year and per application from 2005 to May 31, 2018.

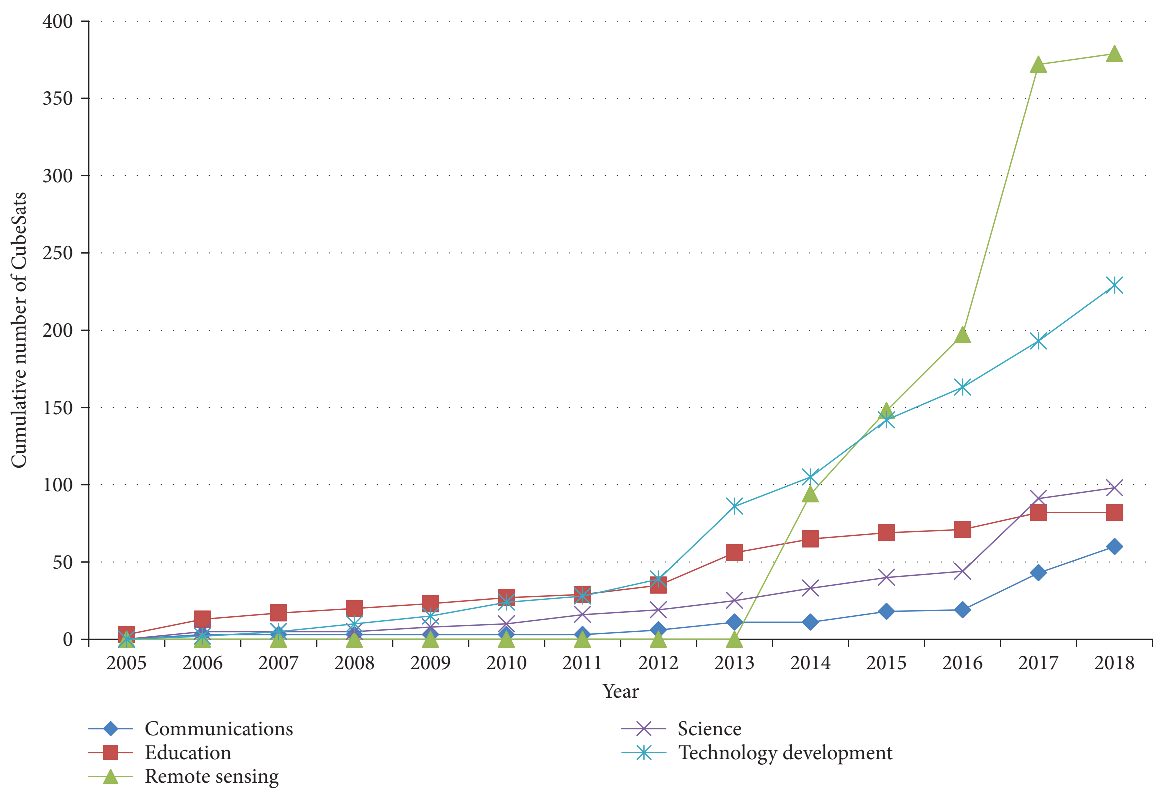

FIGURE 4: Cumulative number of CubeSats launched per year and per end use from 2005 until May 31, 2018.

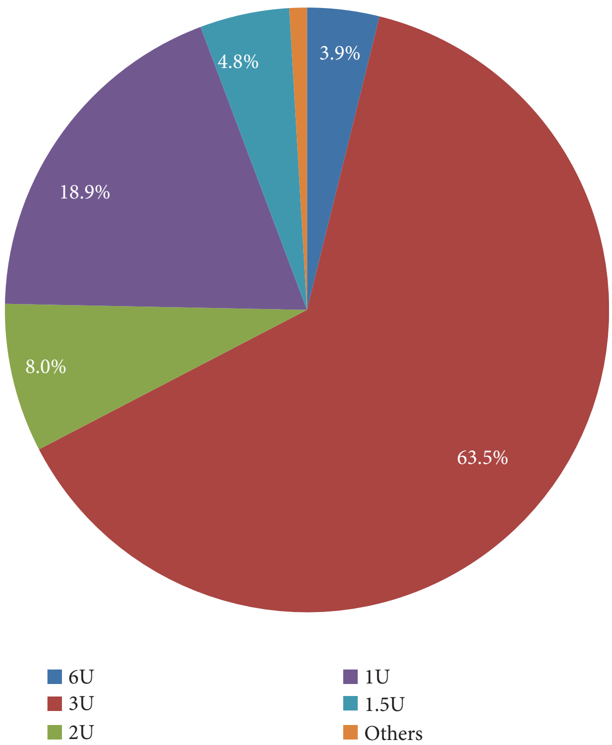

FIGURE 5: Distribution of CubeSats according to their configuration.

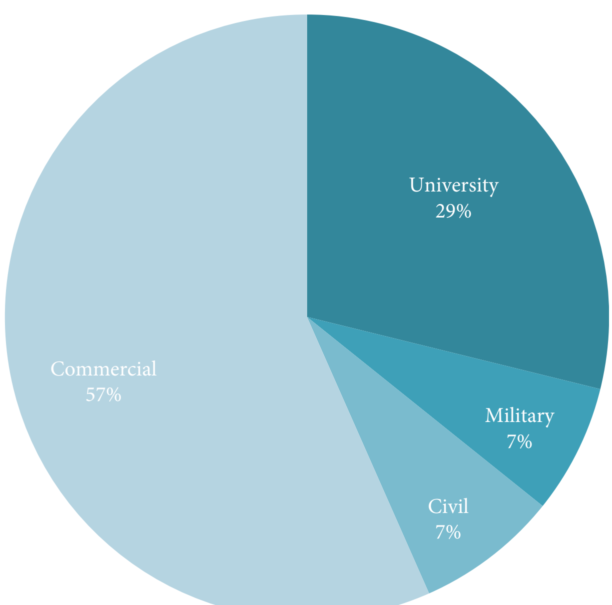

FIGURE 6: Distribution of CubeSats by end user.

launched in 2017. Close to 70 had already been launched and other 285 CubeSats are expected to be launched during 2018, making the total number expected for this year to be more than 350.

Countries which have already launched CubeSats from 2005 to May 31, 2018 are shown in Figure 2, along with their respective number of CubeSats launched and the years they were launched. In this figure, 12 CubeSats which were developed through multinational collaborations are not shown: 2016, Japan/Singapore (1), UK/Algeria (1); 2017, Australia/Canada/US/UK (1), Ecuador/Russia (1), Japan/Malaysia/Bangladesh/Ghana/Mongolia/Nigeria/Philippines/Bhutan (4), Holland/Belgium/Germany/Israel (1), and UK/Israel/Australia (3). These collaborations represent a novel way of involving different countries in space activities.

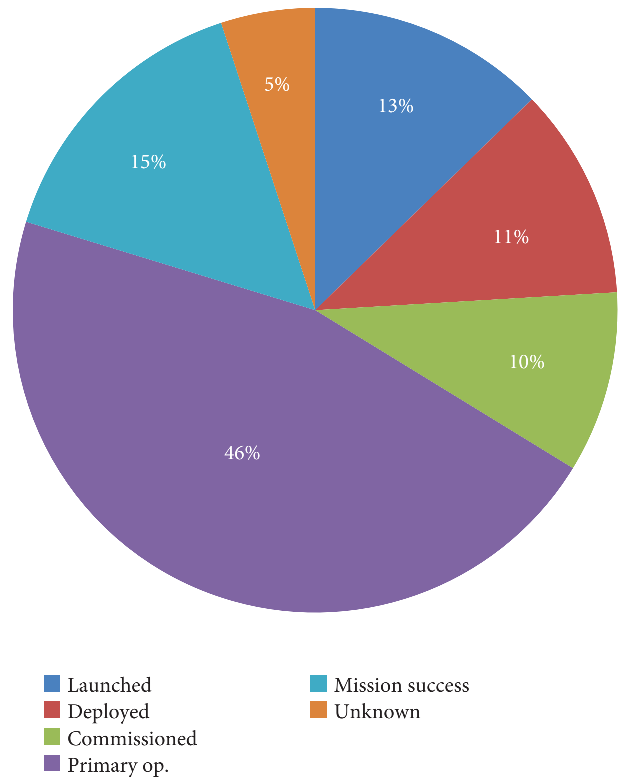

FIGURE 7: Distribution of CubeSats according to their mission status as of May 31, 2018.

3.2. Applications. From Figures 3 and 4, one can notice that Earth remote sensing is the main application to which CubeSats have been devoted to. Earth observation has been an interesting driver for CubeSats (e.g., [22]). Technology demonstration also represents an important fraction of the total number of launched CubeSats. Figure 5 shows the distribution of CubeSats according to their configuration, being 1U, 2U, etc. The most used CubeSat configuration is 3U (about 64%).

In 2013, few CubeSats were used for remote sensing; however, this use currently corresponds to the majority of the launched artifacts. CubeSats offer a new alternative for the Earth observation application and are establishing a growing market for this application. CubeSats with advanced image processing techniques are imaging Earth with resolution comparable to bigger satellites.

3.3. Platform Configuration. Different CubeSat platform configurations are being used to address different needs. The 3U configuration is the most used (64%), while 6U platforms account for about 4%. One interesting fact is the use of the 1.5U configuration on around 5% of the CubeSats.

FIGURE 8: CubeSats mission status according to some time periods as of May 31, 2018.

3.4. End Users. In Figure 6, the distribution of CubeSats according to the application sector is shown. These small devices are leaving academic institutions and becoming an important contributor to the commercial sector. Companies are changing how Earth imaging commerce is done in many different ways by applying CubeSat platforms. Military industries are also becoming interested in developing CubeSats for some applications.

3.5. Mission Status. One of the concerns about the use of CubeSats is their failure rate. CubeSat technology is evolving and new companies are becoming specialized in manufacturing dedicated parts for CubeSats. As a consequence, CubeSats are becoming more reliable, as flight heritage is being built up and the new artifacts are benefiting from it.

In Figure 7, the mission status of all CubeSats launched as of May 31, 2018 is shown. When mission status is indicated as "launched," it means that the satellite has left Earth but it has not been deployed yet (i.e., it might be waiting in the ISS); "deployed" means the CubeSat deployment system worked, but no signal was received from the device after that; "commissioned" means the CubeSat made at least one successful downlink and uplink, but then communication was lost; "primary op." status corresponds to the CubeSats which have accomplished a good part of their mission or the mission is still in progress; "mission success" refers to CubeSats that successfully accomplished their missions and might still be operational.

CubeSats themselves cannot be blamed for all mission failures. Around 20% of all failures occurred either during launch or during the deployment phase. In Figure 8, how the CubeSat mission status has changed over time is presented. One can notice that the success rate of CubeSat missions has increased while the launch failure rate has decreased, although CubeSat failure during the early stages of operation remained practically constant. When a CubeSat

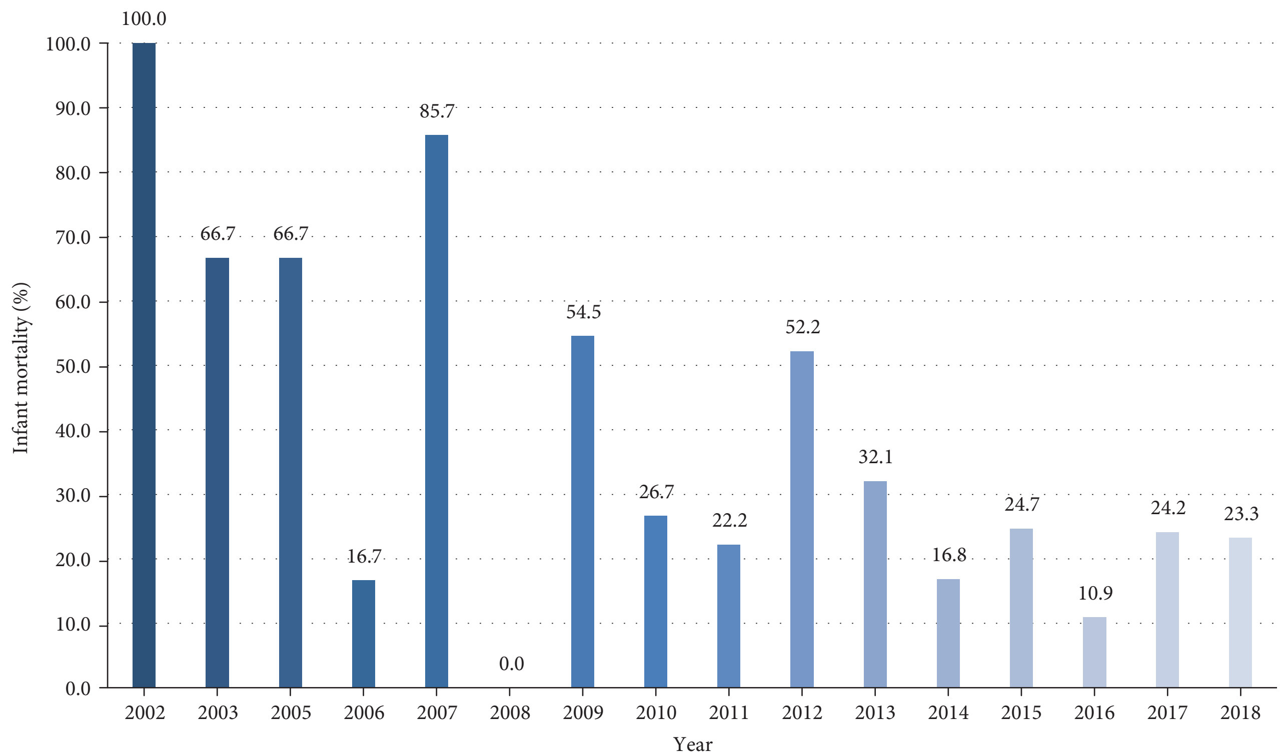

Figure 9: Infant mortality for CubeSats from 2002 up to May 31, 2018 (launch failures excluded).

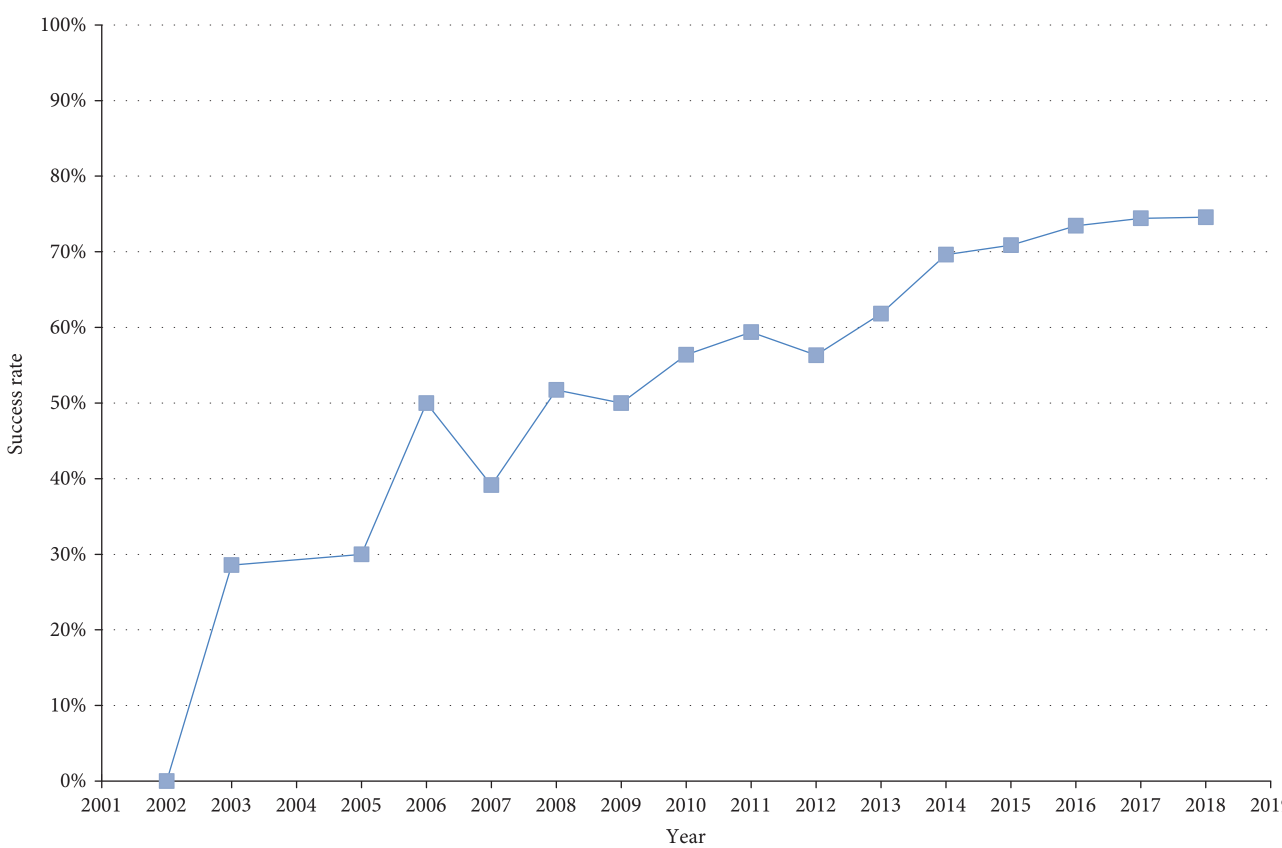

Figure 10: Success rate of CubeSat missions as a function of time.

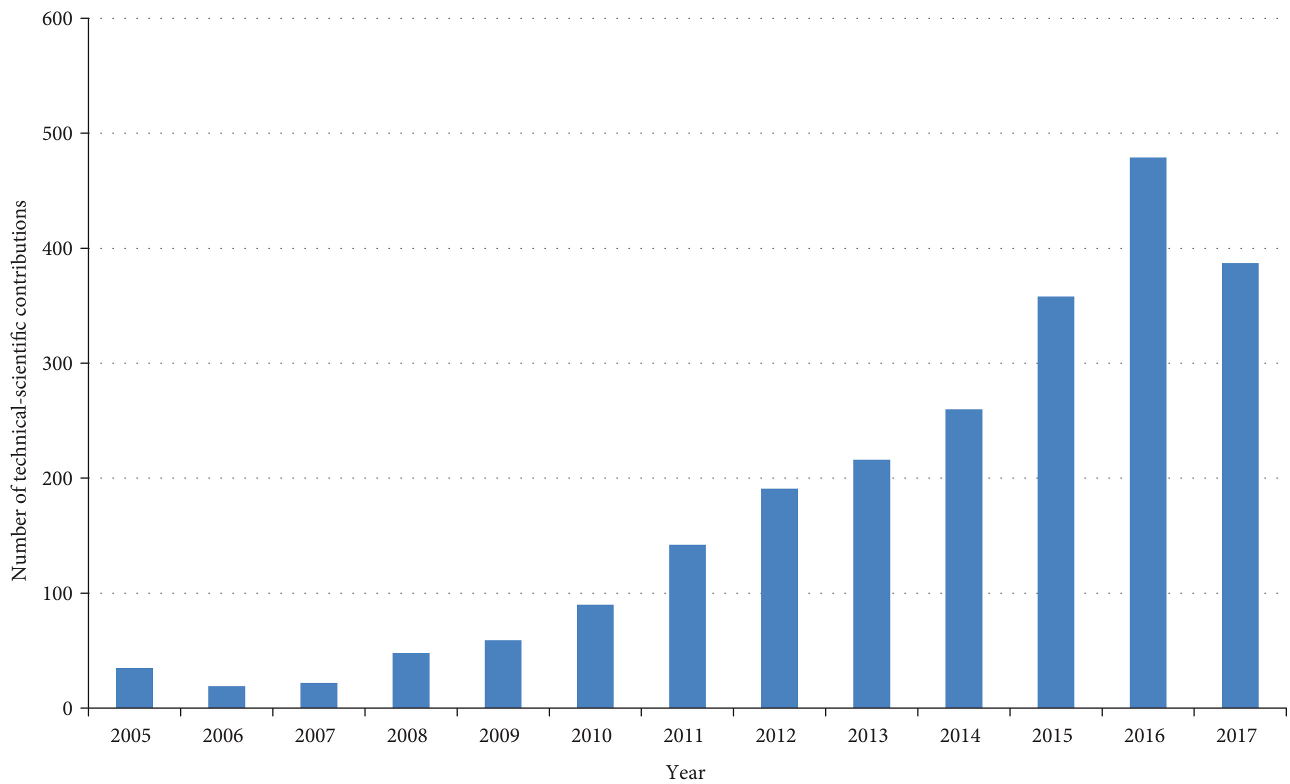

FIGURE 11: Distribution of technical-scientific contributions related to CubeSats between 2005 and 2017, totaling 2306 documents (source: Scopus).

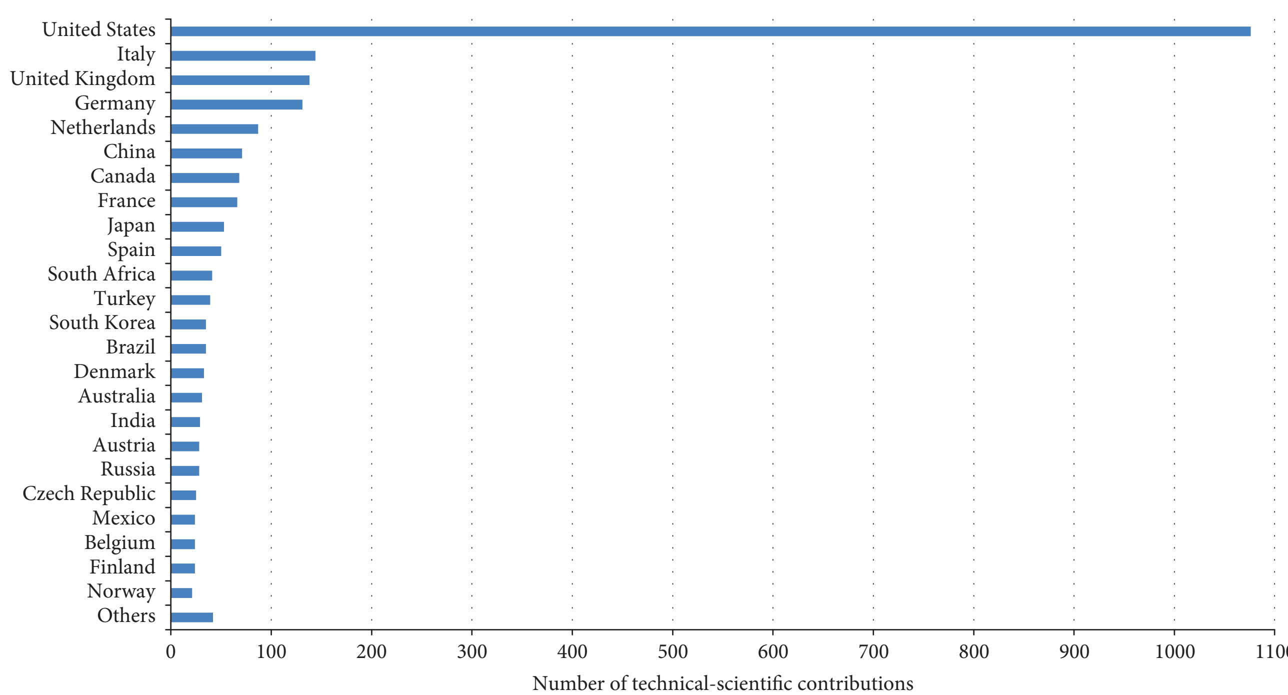

FIGURE 12: Number of technical-scientific contributions per country between 2005 and 2017.

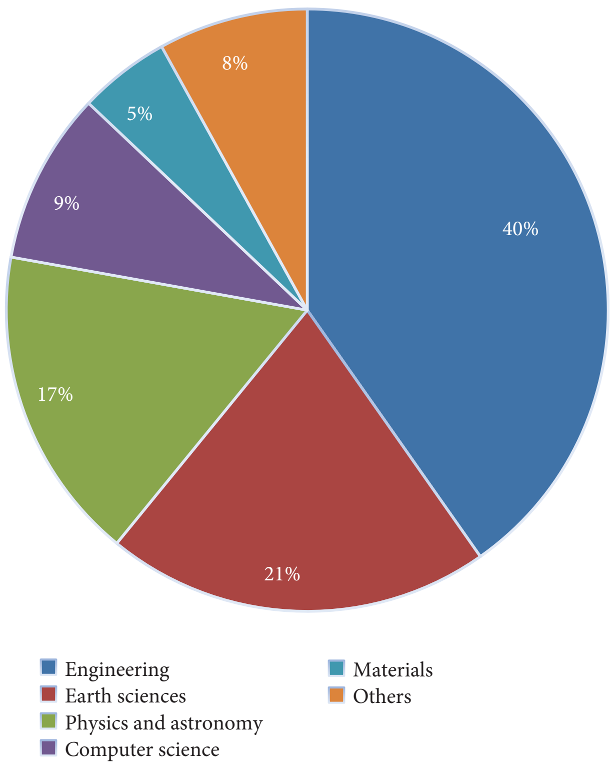

FIGURE 13: Distribution of CubeSat applications by knowledge area.

fails during commissioning or during the early stages, it is said that "it died as an infant". *Infant mortality* has been a big issue for CubeSats (e.g., [23]). Most of them failed as soon as they got into the space environment.

ISO 19683:2017(E) was established aiming to diminish the so-called *infant mortality* of small spacecrafts. From the available data, it is still early to draw any conclusion about the fulfilment of this goal, since this norm was published about a year ago. The data shown on Figure 9 suggest that CubeSat *infant mortality* is decreasing.

As shown in Figure 10, the success rate of the overall CubeSat missions is increasing over time, currently being about 75%. The success rate was estimated by considering CubeSat missions as a Bernoulli experiment, so the success rate is considered as a parameter of a binomial distribution. It was considered a "success" if the CubeSat survived its early operational stages (deployed and commissioned) or, in other words, "it did not die as an infant." Launch failures were excluded.

Some factors will probably improve CubeSat success rate in the near future, like the use of products with flight heritage and CubeSat international standards [24].

3.6. Orbits. The choice of most CubeSat orbits are dictated by the main payloads. These orbit options are usually limited to Low-Earth Orbits (LEO). This is a cheap option for CubeSats. Most CubeSats have been launched to altitudes of 400–600 km and will decay in several months to a few years, which agree with antispace-debris policies and ensures that they are flying below the congested 700–1000 km orbital band. Their orbital decay and lifetimes are essentially predicted by estimating drag forces from atmospheric models (assuming no propulsion thrusters are used). For instance, for CubeSat orbits from around 200 km, decaying is expected in a matter of hours or days; for orbits around 800 km, decaying will take a few hundred years.

3.7. Technical and Scientific Publications. An objective way to assess the interest in CubeSats worldwide is to analyze technical and scientific production related to this platform. Data collected from the Scopus platform show that there is an increasing production of papers related to CubeSats in conferences and refereed journals, as shown in Figure 11. In Figure 12, some countries with at least twenty technical and/or scientific contributions are shown. The areas to which this production refers to are shown in Figure 13.

CubeSats have already proved their value as an educational tool. They are also being used for technology development, as can be seen by the increasing number of engineering articles on this subject.

3.8. Patents. Another indicator of the commercial interest in CubeSat technologies is the number of patent deposits. Over the past seven years, according to the European Patent Office (EPO), this number kept growing at an interesting rate, as shown in Figure 14.

The United States leads with the most patent deposits holding 87% of all deposits, followed by China (6%), Australia (1%), and Russia (1%), according to EPO. Institutions which own most patents are presented in Figure 15.

3.9. Launchers. In general, CubeSats are being launched through piggyback. As secondary payloads, they have been conditioned to primary mission orbits or to International Space Station availability to launch them. Surveys of small satellites and CubeSat launches can be found, for instance, in Wekerle et al. [25] and Polat et al. [26], respectively. Figures 16 and 17 show a panorama of the main launchers used for CubeSats and their respective companies. PSLV is playing an important role in CubeSat launchings; until May 31, 2018, it is the record holder for the number of CubeSats launched by a single rocket.

Currently, there is no dedicated CubeSat launcher that can be used on a commercial basis. This fact restrains the use of CubeSats for several applications and, as a consequence, creates a sort of bottleneck for the increase of the industry associated with such artifacts. There are, though, some initiatives to develop dedicated CubeSat launchers. For instance, on February 3, 2018, a JAXA SS-520-5 rocket successfully launched a 3U Tricom-1R CubeSat into a slightly higher orbit than planned. This achievement placed it as the "smallest orbital rocket".

4. CubeSat Launching Forecast

Despite the drop in launching numbers in 2015 and 2016, in 2017 the trend of exponential growth presented up to 2014 was recovered. If the launching number keeps following the current tendency, one thousand CubeSats are expected to be launched per year by 2021, as shown in Figure 18 (solid line).

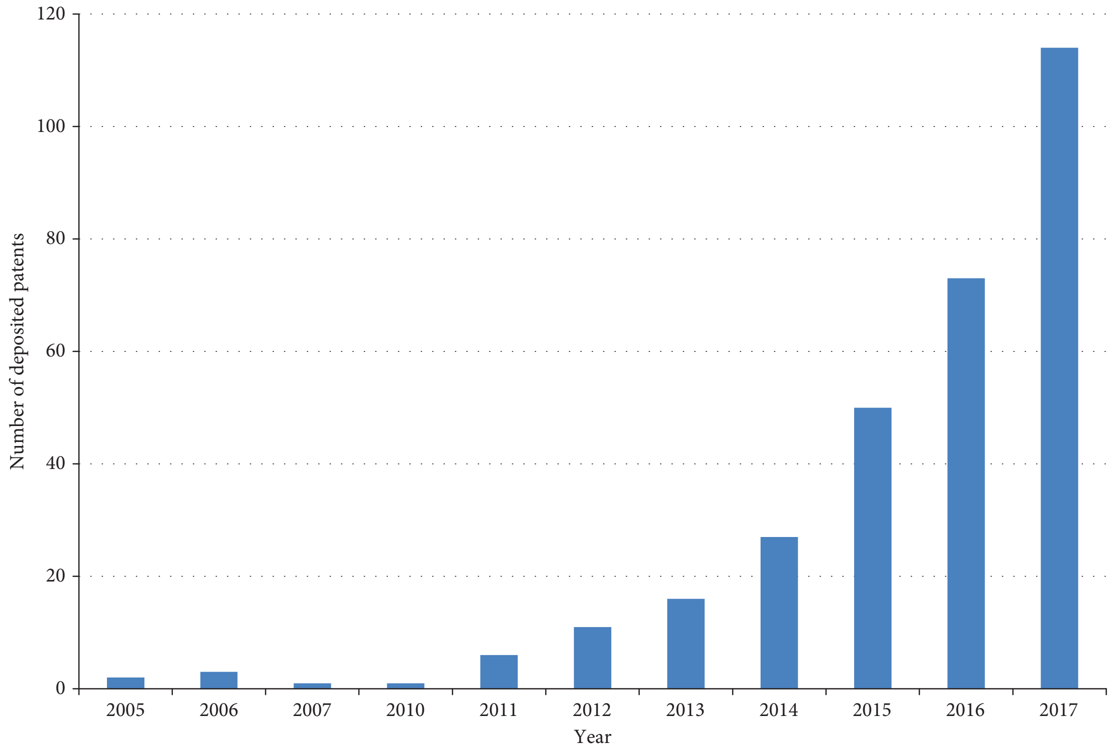

Figure 14: Number of deposited patents related to CubeSats between 2005 and 2017, totaling 304 patents (source: European Patent Office).

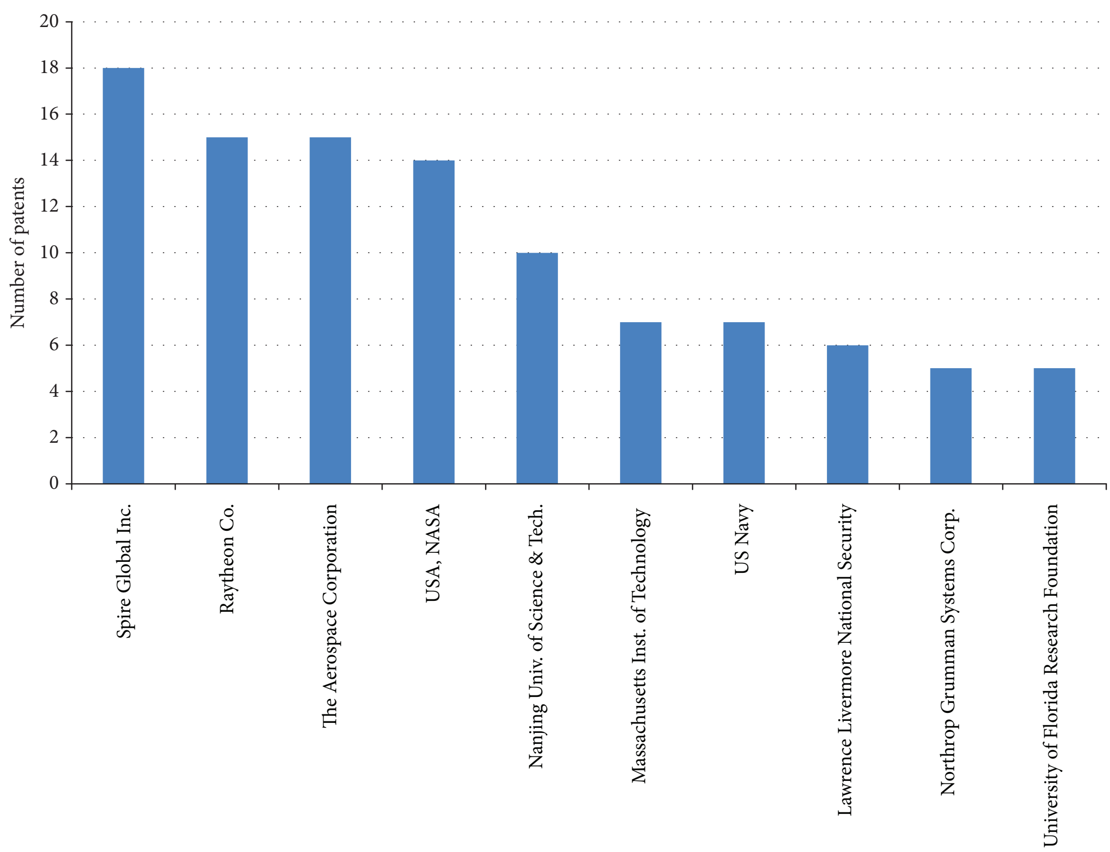

Figure 15: Main CubeSat patent holders, until December 2017 (source: EPO).

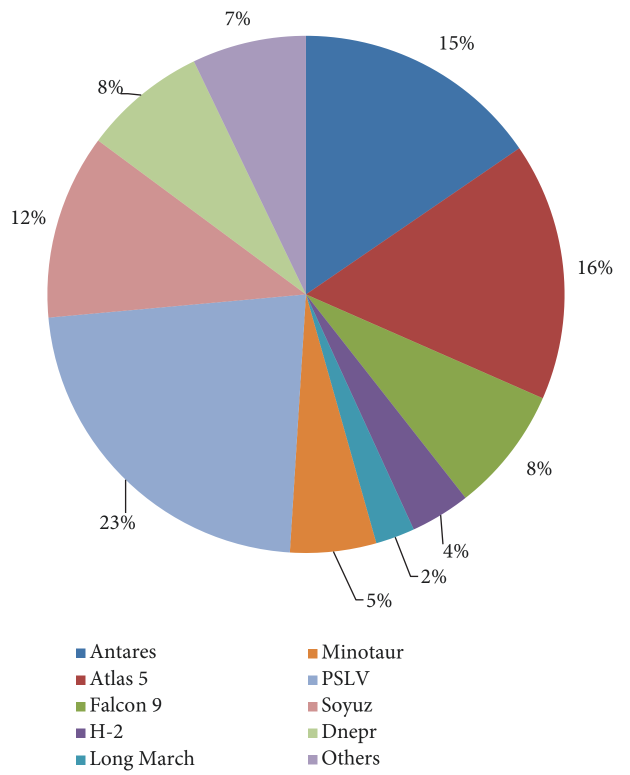

FIGURE 16: Main CubeSat launchers.

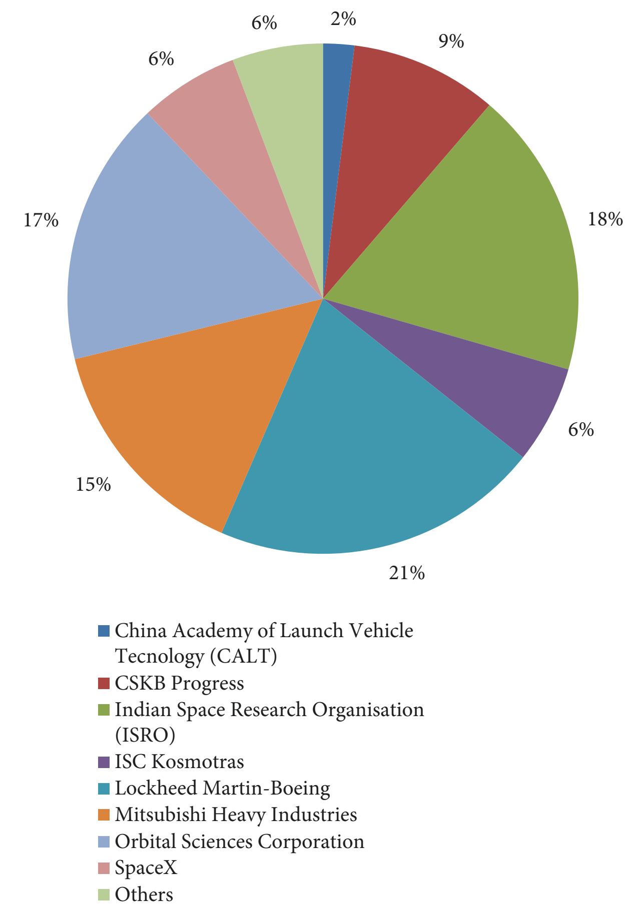

FIGURE 17: Main CubeSat launchings companies/institutions.

This estimate was done using a logistic model, described by the following expression:

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right), \qquad (1)$$

where N is the total number of CubeSats launched, r is the growth rate, and K is the carrying capacity, which can be understood as a market demand. A Markov Chain Monte Carlo approach was used to estimate r and K parameters. N_0 was set up for corresponding to the number of launchings up to 2007. The shaded area covers 95% confidence interval for such a tendency.

According to our estimate, and based on the information of future launchings, the thousandth CubeSat is expected to be launched by late 2018-early 2019.

5. Final Remarks

The number of CubeSat launchings increased from one CubeSat launched every 4 months in 2005, to almost 24 CubeSats launched every month in 2017. CubeSats were the majority of the approximately 300 satellites of the nano- and microsatellite categories launched in 2017. From January to May of 2018, almost 70 new CubeSats had been launched or were onboard ISS to be injected into orbit. According to the Satellite Industry Association [27], 45 of the 79 satellites launched by the US in 2016 were CubeSats. As shown in this paper, the number of technical-scientific publications and the number of patent deposits related to CubeSats showed considerable increase. These facts indicate that there is a global interest related to the use of CubeSats to address different needs, like Earth remote sensing and scientific applications. Interestingly, several CubeSats are being developed to provide Earth observation services by private companies.

One of the advantages of the open and standardized CubeSat architecture is that it provides opportunities for developers to rapidly produce space systems. In addition, the use of standard launching modules for CubeSats, like Poly Picosatellite Orbital Deployer (P-POD) and Space Shuttle Picosatellite Launcher (SSPL), facilitates the access of new players to space activities. This way of launching spacecraft in orbit represents an interesting innovation in the space sector. Moreover, the diminishing costs of CubeSat missions is becoming possible because of the fast technology advancements in microelectronics, coupled with the intense use of COTS components. The miniaturization of sensors and actuators allowed, for instance, the development of attitude determination and control systems for CubeSats (e.g., [28]). Innovations like foldable lightweight optics, solar panels, and antennas will also boost CubeSat usage (e.g., [29–32]).

Despite these advantages, there is a concern that CubeSats may increase the number of space debris. In order to mitigate this potential problem, several debris removal

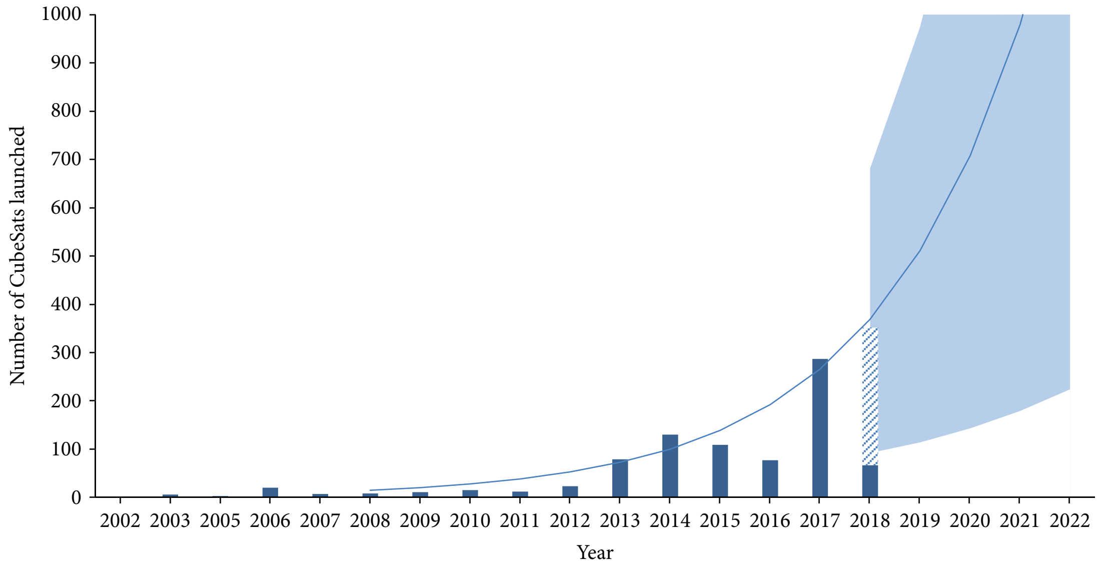

Figure 18: Best fit for the number of CubeSats launched per year (solid line). The shaded area represents 95% confidence interval for future launchings.

possibilities are being suggested [33, 34]. The adoption of the International Code of Conduct for Outer Space Activities and ISO 24113:2011 (which defines the primary space debris mitigation requirements) by CubeSat developers is also a step towards addressing this problem.

CubeSats represent an interesting option in the small satellite category to countries and institutions to get their needs of space applications fulfilled [35]. CubeSats are also being used to promote international collaboration in space [36]. CubeSats will probably play an important role in the overall international space context in the near future.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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