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Status and Trends of Smallsats and Their Launch Vehicles — An Up-to-date Review

Timo Wekerle[1], José Bezerra Pessoa Filho[2], Luís Eduardo Vergueiro Loures da Costa[1], Luís Gonzaga Trabasso[1]

ABSTRACT: This paper presents an analysis of the scenario of small satellites and its correspondent launch vehicles. The miniaturization of electronics, together with reliability and performance increase as well as reduction of cost, have allowed the use of commercials-off-the-shelf in the space industry, fostering the Smallsat use. An analysis of the launched Smallsats during the last 20 years is accomplished and the main factors for the Smallsat (r)evolution, outlined. Based on historic data, future scenarios for different mass categories of Smallsats are presented. An analysis of current and future launch vehicles reveals that we are currently in a phase of transition, where old launch vehicles get retired and new ones enter the market. However, the satellite launch vehicle business has been established to carry payloads of thousands of kilos into low Earth orbit and has not adjusted itself to the market of Smallsats. As a result, there is only 1 launch vehicle for dedicated Smallsat launches commercially available, but it carries a high price tag. Several small low-cost launch vehicles under development are identified and the challenges to overcome, discussed. Since these small launch vehicles have similar complexity as huge launch vehicles, high development costs are intrinsic, leading to a high specific price (USD/kg payload).

KEYWORDS: Small satellites, Launch vehicles, Access to space.

INTRODUCTION

During the past 30 years, electronic devices have experienced enormous advancements in terms of performance, reliability and lower prices. In the mid-80s, a USD 36 million supercomputer was capable of executing 1.9 billion operations per second and its selling was restricted. Today, an off-the-shelf tablet computer can execute 1.6 billion operations per second and it can be bought via Internet for USD 300. Unlike the 1985's supercomputer, which weighted 2,500 kg and consumed 150 kW, a tablet computer weights around 0.5 kg and requires 0.01 kW (Osseyran and Giles 2015). Such an evolution is evident in day-to-day life. But how the space sector has benefited from such an evolutionary process in terms of satellites and launch vehicles?

The use of COTS to build Smallsats started in the mid-70s at the University of Surrey, which launched its first satellite (UoSat-1) in 1981. The interest of Smallsats increased in the following decade when academic organizations started to design and build their own satellites. As the microelectronics evolved, the interest grew and reached a milestone with the creation of the Cubesat standard in 2001. Nowadays, it is possible to purchase the whole Smallsats, hardware and software, on the internet.

The present research reveals that about 1/3 of the 2,500 satellites launched in the past 20 years had a wet mass (including fuel) below 500 kg, subsequently called Smallsats. The amount of Smallsats launched in the last 5 years is nearly equivalent to the accumulated amount of the 15 years before. Therefore, what has begun as a research and development project has evolved and found commercial applications in areas like communications and remote sensing. It is not clear how far

1.Departamento de Ciência e Tecnologia Aeroespacial – Instituto Tecnológico de Aeronáutica – Divisão de Engenharia Aeronáutica e Mecânica – São José dos Campos/SP – Brazil. **2.**Departamento de Ciência e Tecnologia Aeroespacial – Instituto de Aeronáutica e Espaço – Divisão de Sistemas Espaciais – São José dos Campos/SP – Brazil.

Author for correspondence: Timo Wekerle | Departamento de Ciência e Tecnologia Aeroespacial – Instituto Tecnológico de Aeronáutica – Divisão de Engenharia Aeronáutica e Mecânica | Praça Marechal Eduardo Gomes, 50 – Vila das Acácias | CEP: 12.228-900 – São José dos Campos/SP – Brazil | Email: timotw@ita.br

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this miniaturization process will lead to, but in many cases Smallsats can already accomplish what only big satellites could do in the past.

Satellites are being deployed into orbit by satellite launch vehicles (LVs) and so far, this is being realized by huge launch vehicles capable of carrying thousands of kilogram payloads. Usually, since LVs have not experienced a significant reduction in size, Smallsats fly as secondary payload, so called piggy back. The use of converted Intercontinental Ballistic Missiles (ICBMs) enabled cheap access to space through the rideshare concept. Another possibility is the launch from the International Space Station (ISS). Nowadays, there is only 1 commercial Micro-LV available for dedicated launch of Mini- and Micro-satellites, permitting the definition of orbit and launch date. However, it carries a high price tag. To address the promising market of Smallsats, there are several Small- and Micro-LV developments on the way.

It is worth mentioning that Micro-LVs are not new. In the very beginning, orbital spaceflight began with Micro-LVs. The American Vanguard put a 11-kg satellite into orbit in 1959. The Japanese Micro-LV Lambda 4S, in 1970, was capable of putting a 24-kg Smallsat into orbit. In the meantime, the satellites got bigger caused by more and more sophisticated payloads and, consequently, the LVs increased their payload capacity. However, due to technological advancements, satellites nowadays become smaller, but this trend is not being followed by reduction of payload capacity and size of the LVs.

By an extensive literature review and the use of a database of Smallsats from 1995 to 2014, the aim of this study was to provide the current status and trends of Smallsats and small LVs, including their features, challenges and prospects.

DEFINITIONS

A classification for Smallsats and LVs established by the authors is defined in Table 1. Besides the Smallsat classification, Cubesats are defined in the *CubeSat Design Specification* (Cal Poly 2015) as Units (U) with a wet mass of m < 1.33 kg and dimensions of 10 × 10 × 10 cm. Commonly-used Cubesats have form factors of 1-3U and 6U. The emerging Pocketcube standard defines a satellite with a wet mass of m ≤ 0.125 kg and dimensions of 5 × 5 × 5 cm (Deepak and Twiggs 2012).

Table 1. Classification for Smallsats and Launch vehicles.

Smallsats	Wet Mass
Pico-Satellite	≤ 1 kg
Nano-Satellite	1 – 10 kg
Micro-Satellite	11 – 100 kg
Mini-Satellite	101 – 500 kg
Launch Vehicles	**Payload Capacity**
Micro-LV	≤ 500 kg
Small-LV	501 – 2,000 kg
Medium-LV	2,001 – 20,000 kg
Heavy-LV	> 20,000 kg

RELATED RESEARCH

In 1996, Stoewer (1996) advocated the use of Smallsats and claimed that the times of technology push were over and user pull was the paradigm. Twenty years later, the Smallsat market is booming, which can be confirmed not only by the number of Smallsats launched, but also by the increasing amount of conferences in this area, including: AIAA/USU Conference on Small Satellites; ESAs Small Satellites and Services Symposium; Interplanetary Small Satellite Conference; IAA Symposium on Small Satellite for Earth Observation; and the International Telecommunication Union (ITU) Symposium and Workshop on Small Satellite Regulation.

What began as scientific and research activity is now also catching interest of private initiatives. As a result, nowadays, several non-profit and for-profit organizations release forecasts on a regular basis. Since 2013, the Federal Aviation Administration (FAA) includes a Smallsat section in its annually Commercial Space Transportation Forecasts (FAA 2013). The *Smallsat Report* is published by Newspace Global since 2014 (NSG 2014), whereas Spaceworks offers market assessments and forecasts (Buchen and de Pasquale 2014). In 2015 Euroconsult debuted its *Prospects for the Small Satellite Market* (Euroconsult 2015).

By looking at the satellite LVs, in 1995, Naumann (1995) identified 34 projects of satellite LVs with payload capacity of under 1,000 kg. Ten of them were expected to be in operation by the year 2000. Unfortunately, it did not happen and nowadays there are few options for dedicated Smallsat launches available. The current literature for small LVs miss a critical analysis of the existing ones, in terms of realistic and/or up-to-date launch prices and availability. Crisp *et al.* (2014) made a review of current and future LVs. Since then, the new ones entered in operation, new developments were announced, others were already canceled and the prices have changed.

Despite the amount of studies published in the area of Smallsats and LVs, the authors perceived that none of the previsions related to Small-LVs were carried out. Furthermore, there is a perspective that there will be a boom in the Smallsat market whose realization will depend on several factors and challenges, which are analyzed in this paper.

SMALLSATS

SMALLSAT DATA ANALYSIS

Based on the Electronic Library of Space Activity (ELSA) database from Futron Corporation (2013), as well as a research conducted by the authors, 863 Smallsats were identified between 1995 and 2014. In the following sections an analysis is conducted based on their wet mass; launch year; payload use; manufacturer country; and launch vehicle.

The quantity of Smallsats, categorized by wet mass, is illustrated in Fig. 1, where 3 important phases can be identified. The first phase goes from 1995 to 2000, with a peak in 1998 and 1999. The driving force was the deployment of Orbcomm (Micro-satellites) and Globalstar (Mini-satellites) constellations for commercial communication services. They represent about 65% of all Smallsats launched in that phase. Together, these companies launched 85 of their first-generation Smallsats. During the second phase, between 2001 and 2012, on average 30 Smallsats where launched per year. During this phase, the Cubesat standard, created in 2001, was first successfully tested in orbit in 2003. Since then, several universities, companies and institutions started their Cubesat projects. Taking an average development cycle between 1.6 and 3.8 years (Richardson *et al.* 2015), 20 Cubesats were launched in 2006. Unfortunately, 14 of them were launched on a single launch of a DNEPR launch vehicle, which failed. Nonetheless, this incident could not stem the tide.

The third phase started in 2013, being characterized by large growth rates of Nano-satellites. The following events may be highlighted for 2013: (a) The amount of Nano-satellites varied from 24 in 2012 to 81 in 2013; (b) 68% of all Smallsats were Cubesats; (c) The number of scientific Smallsats doubled; (d) The amount of military payloads launched was 4 times higher than in 2012. The same trend continued for 2014 as the number of Nano-satellites increased to over 123. It is worth mentioning that, in 2014, Planet Labs alone launched 93 commercial 3U Cubesats for remote sensing.

An overview of Smallsat wet masses, between 1995 and 2014, is shown in Fig. 2, where the major constellations are highlighted: 86% of all non-constellation Smallsats have less than 200 kg of wet mass and 39% have less than 10 kg. It should be noted that the first generation of Globalstar satellites had a mass of 450 kg. The second generation of Globalstar satellites, launched since 2010, have a wet mass of 650 kg and no longer belong to the Smallsat class.

The share of payload applications is depicted in Fig. 3. The 4 major applications are: Communication; Research and Development; Scientific; and Remote Sensing. Research and Development has the highest share of 31%, being mainly built and operated by Civil, Non-Profit and Military organizations. The majority of the 27% share of communication Smallsats come from the commercial (Globalstar and Orbcomm), government (Gonets) and military (Kosmos) constellations. Remote Sensing Smallsats represent 18% and include the commercial

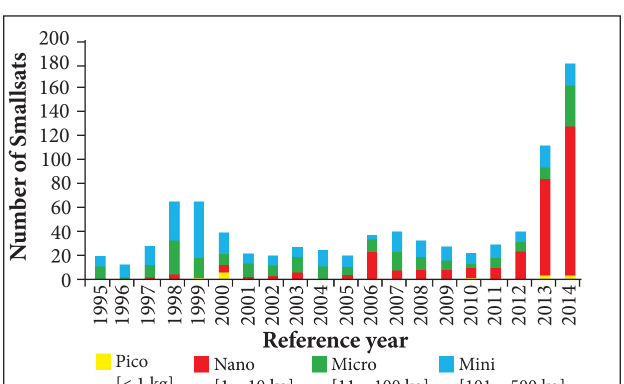

Figure 1. Smallsats launched from 1995 to 2014 ordered by launch year and class.

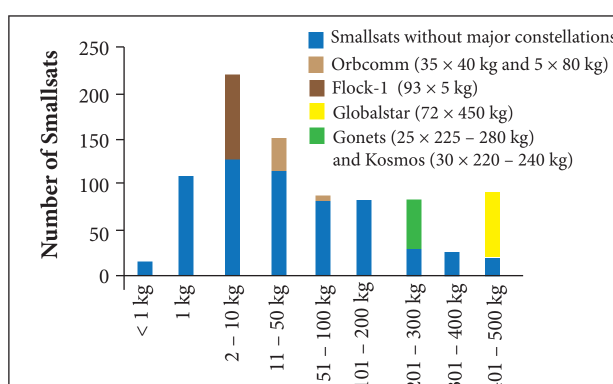

Figure 2. Histogram of Smallsats launched from 1995 to 2014 ordered by mass. Constellations are marked with color.

3U Cubesat Flock-1 constellation. The quantity and mass of these constellations are highlighted in Fig. 2. An important feature of Fig. 4 is that half of the Smallsats launched between 1995 and 2014 have commercial and military applications. However, it should be pointed out that such a result was made possible through advancements of Scientific and Research and Development Smallsats, represented in Fig. 3 with 17 and 31% share, respectively.

Between 1995 and 2014, 144 military Smallsats were launched. The US and Russia alone have launched 72 and 40, respectively. In the case of US, the share of military Smallsats is 16%, whereas in the case of Russia, it is 44%.

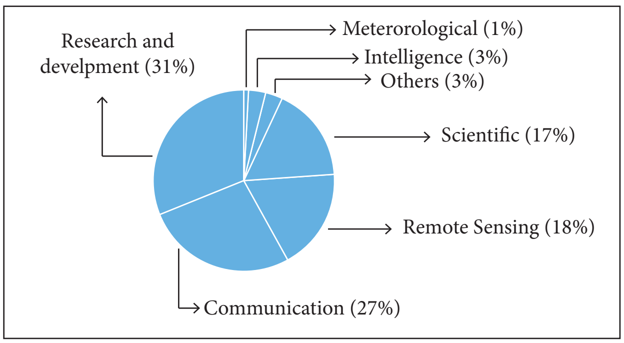

Figure 3. Share of payload applications of Smallsats.

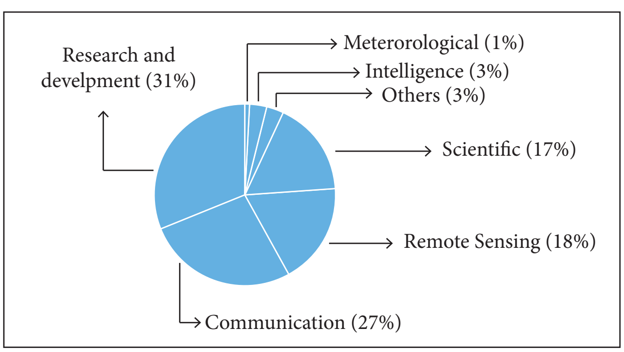

Figure 4. Type of payload operator of Smallsats.

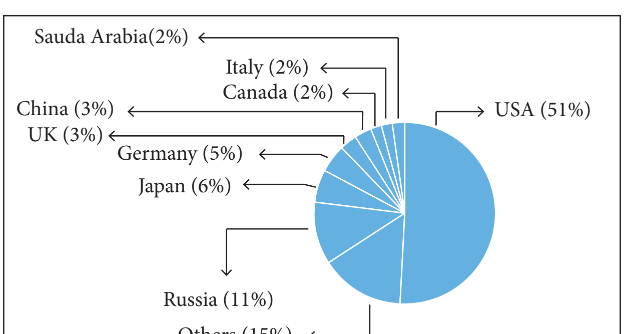

Figure 5. Share of Smallsat manufacturer countries.

However, by considering all launched Smallsats, the US is responsible for manufacturing more than the half of them (Fig. 5); 1/3 of the manufacturing market was shared by Russia, Japan, Germany, China, UK, Saudi Arabia, Canada and Italy. Other 37 countries are accountable for the 15% share of Smallsat manufacturing.

(R)EVOLUTION OF SMALLSATS

According to Naumann (1995), in 1995, Euroconsult identified 280 – 320 Smallsats for the following 12 years; the ELSA database revealed 417 Smallsats launched in that period. Only in 2014, 181 Smallsats were launched. Such an evolution may suggest a Smallsat revolution, which was made possible by:

- Platforms for testing new technologies: Smallsats enable cheaper and faster qualification of new systems and subsystems in the space environment.
- Reduced Life Cycle: since Smallsats have simpler architecture and make use of COTS, the development phase is shorter, leading to more frequent mission opportunities and faster return. The life cycle can be adjusted to a level compatible with technological upgrades.
- Standardization: the standardization of satellite buses and its components reinforces the use in Smallsats and makes satellite technology accessible.
- Single Purpose: by restricting missions to a particular purpose in contrast to multi-payload satellites, mission complexity is reduced. This results in lower management cost and faster development.
- Up-to-date Technology: unlike traditional satellites that use space-qualified items with technological gaps of up to 10 – 20 years to the state-of-the-art technologies (Bonyan 2010), Smallsats use in large part COTS with up-to-date technologies, including, amongst others: Micro Electromechanical Systems (MEMS); Active and passive de-orbit; Use of rapid prototyping; On-orbit servicing; Plug-and play systems; Improvement of resolutions; In-orbit autonomy; Attitude knowledge and control; and On-board power.
- New Applications: the concept of constellation and formation flying of Smallsats enables global and simultaneous observation of Earth and space with short revisit times.

- Competitiveness with ground-based technologies: Smallsat services have the potential of competing with ground-based technologies. Shorter development times and up- to-date technologies of Smallsats may convince investors in favor of space-based technologies (FAA 2012).
- Competitiveness with conventional satellites: New constellations will force geostationary satellite operators to lower their prices (Selding 2015a). There are start-up companies working in this area. They have slim structure which allow them to be very competitive. Planet Labs, for example, has shown that it is possible to develop, build and operate a high number of satellites (> 100 Smallsats) with a small team (< 100 employees). Thus, besides the technical challenges mentioned before, the large space companies will have to modify their business model.
- Accessibility: affordable access to space can be accomplished by Smallsats for many new entering space fairing nations (Argoun 2012; Wood and Weigel 2014). According to the concept of the space technology ladder established by Wood and Weigel (2012), building Smallsats for LEO is the next step, after creating a national space agency.
- International Cooperation: recognizing the economic and social benefits from space activities, the United Nations support Smallsat programs in developing and emerging countries. A worldwide Cubesat program in order to achieve a sustainable global space exploration was proposed by Ansdell *et al.* (2011). Another example is the European Union which supports the QB50 program, including 27 countries worldwide.

The combination of the aforementioned items has led to a significant decrease of Smallsat cost and an increase of Smallsat use. Aware of these new possibilities, the private sector has invested in the Smallsat business. New start-ups with creative and "out-of-the-box" ideas emerged. In addition, companies like SpaceX, Samsung, Google, Facebook, Intelsat, Coca-Cola, Virgin Group and Qualcomm have shown interest in using Smallsats to provide global Internet service (Selding 2015b).

MARKET FOR SMALLSATS

In the recent years, several organizations have addressed the Smallsat market. In 2008 and 2010, Futron Corporation (Foust *et al.* 2008; Foust 2010) identified 6 promising markets for Smallsats with wet masses of 100 – 200 kg, namely: Military science and technology; Intelligence, Surveillance and Reconnaissance; Remote site communications; Polling of unattended sensors; Earth observation; and Environmental monitoring. The forecast for 2010 was of 39 to 76 Smallsats per year, with revenue between USD 300 million and USD 570 million.

Another study conducted by NewSpaceGlobal in 2014 predicted about USD 1 billion worldwide revenue for 2014 (NSG 2014), and, for 2015, the SmallSat Report predicted of over USD 2.5 billion, including more than 400 payloads (< 500 kg) (NSG 2015).

Spaceworks forecasted in their 2016 Nano/Microsatellite Market Forecast as many as 3,000 Nano- and Micro-satellites (< 50 kg) to be launched between 2016 and 2022 (Doncaster and Shulman 2016).

In the inaugural issue of Prospects for the Small Satellite Market, Euroconsult estimated a market value to develop and launch Smallsats (< 500 kg) of about USD 7.4 billion in the period between 2015 and 2020. This revenue was said to be the result of an estimate of 510 Smallsats, including 140 of 14 different constellations (Euroconsult 2015). In the second edition, Euroconsult forecasted 3,600 Smallsats with a total market value (manufacture and launch) of USD 22 billion expected to be launched between 2016 and 2025 (Euroconsult 2016).

Since the definition of Smallsats, revenue and period is not always clear and differs from study to study, it is very difficult to verify if the predictions become true. The global market of space business enclosed USD 335.3 billion in 2015 which included USD 16.6 billion for the satellite manufacturing industry. Cubesats were responsible for less than 1% of the revenue for satellite manufacturing (< USD 150 million) (Satellite Industry Association 2016).

Eventually, Smallsats are now becoming a booming commercial market with several applications, including: Air and maritime monitoring (ship detection, oil spill, illegal fishing); Communications; Logistics; Insurance risk sector; Real time property survey; Security; Land use monitoring; Agricultural monitoring (optimization like watering times or fertilizer application); Food security; Surface water, weather and climate; Disaster monitoring (seismic, storm, natural disaster, sea ice etc.); Space weather, affecting satellite navigation and its applications; Traffic monitoring; Deforestation monitoring; Natural resource management; Human and animal behavior; and Asset tracking. Some of the current and announced constellations are listed in Table 2.

Table 2. Overview of deployed (from 1995 onwards) and announced Smallsat constellations

	Constellation name (prganization, country)	Number of deployed satellites	Planned number of satellites	Wet mass	Application	First satellite deployment
Operational Constellations	(Koudelka 2015)	6	6	8 kg	Astrophotometry of stars	02/2013
	Disaster Monitoring Constellation (DMC International Imaging International) (Kramer 2016b)	8	8	50-268 kg	Emergency Earth imaging for disaster relief 2.5 m and 5 m GSD	11/2002
	exactView Constellation (exactEarth, Canada) Macikunas and Randhawa 2012; Miler and Bujak 2013)	10	10	100 kg	Automatic Identification System (AIS)	07/2012
	Flock-1 (Planet Labs, US) (Safyan 2015; Kramer 2016a)	99	Up to 500	3U Cubesats	Earth observation with 3-5 m GSD	01/2014
	Globalstar (Globalstar, US) (Richharia and Westbrook 2010)	72	72	450 kg	Satellite phone and low-speed data communication	02/1998
	Gonets D1 and M (Government, Russia) (Zak 2016a)	12/10	12/18	225-280 kg	Store and dump communication	02/1996, 12/2005
	Kosmos (Military, Russia) (Zak 2016b)	30*	-	220-240 kg	Various, military	-
	Orbcomm OG1 and OG2 (Orbcomm, US) (Spaceflight101 2016)	35/6	35/18+30	40/172 kg	Machine-to-machine communication	04/1995, 06/2008
	Rapideye (BlackBridge AG/Planet Labs, Germany/US) (Sandau *et al.* 2010)	5	5	150 kg	Multispectral imagery with 6.5 m GSD	08/2008
	Sense and Stratos (Spire, UK/US) (Barna 2015)	17	20/125	3U Cubesats	Maritime intelligence and weather data	08/2013, 2015/2018
	Terra Bella Constellation (Google, US) (Murthy *et al.* 2014)	7	24	120 kg	High-resolution Earth observation with ≤1 m GSD	11/2013, 2016
Constellations under development/announced	BlackSky Constellation (BlackSky Global, US) (Blacksky Global 2016)	1	2/4/60	50 kg	Global satellite imagery with 1 m GSD	2016/2019
	CICERO (GeoOptics, US) (Wagenen 2016) (Jasper et al. 2013)	0	6/12/24	100 kg	Climate and atmosphere observation	2017
	UrtheDaily and OptiSAR (UrtheCast and OmiEarth, Canada and US) (Wood 2016)	0	8 / 16	Smallsats	Optical and synthetic aperture radar with 1.1 and 5.5 m GSD	2017-2020
	LeoSat Constellation (LeoSat, US) (LeoSat™ 2017)	0	78	Smallsats	High-speed data transfers using intersatellite links	N/A
	N/A (OneWeb, US) (Foust 2015)	0	648-900	125-200 kg	Broadband Internet connection	2018-2019
	PlanetiQ Constellation (PlanetiQ, US) (David 2016)	0	12/18	6U Cubesats	GPS radio occultation for weather data	2017
	N/A (Samsung, Multinational) (Khan 2015)	0	4,600	Micro-Satellites	Broadband Internet connection	N/A
	N/A (SpaceX, US) (Selding 2015b)	0	4,000	Smallsats	Broadband Internet connection	N/A
	QB50 The von Karman Institute (Scholz 2015)	0	50	Cubesats	*In-situ* measurements in the lower thermosphere	2017
	Satellogic Constellation (SatellogicArgentina/US) (Henry 2016)	2	6/16/300	35 kg	Real-time imaging of the entire Earth with 1 m GSD	04/2014, 2017

*Kosmos satellites were deployed in the period between 1995 and 2014. Part of these Smallsats may belong to military satellite constellations, however, there is a Russian policy of assigning Kosmos names to all military satellites reaching orbit.

CHALLENGES TO OVERCOME

The era of Smallsat technology was initiated by research institutes, universities and start-ups. Comparing the exponential increase of performance already achieved by these players, the entrance of multinational corporations with huge capital may multiply these efforts. Amongst others, the following challenges will have to be overcome:

- Telemetry, Tracking and Command (TTC): Smallsat constellations require new technologies regarding TTC (Ubbels 2015). Networks for ground and space segment and onboard autonomy are required. Distributed systems using formation flying satellites might use synergy of payloads on-board of different satellites instead of a multiplying effect of constellations in order to enhance coverage (Sandau 2010). Open systems, data sharing, and common TTC need to be studied and advanced (Taverney 2015). If the number of predicted Smallsats and constellations become true, it will be of paramount importance to control them.
- Micro-propulsion: new propulsion systems with low mass fraction, high specific impulse and high Delta-v are required for propulsion of Smallsats for deployment, station keeping and formation flying. NASA Space Technology Roadmaps 2012 (Steering Committee for NASA Technology Roadmaps; National Research Council of the National Academies 2012) identified the lack of micro-propulsion as a roadblock and declared it one of its top priorities. Several micro-propulsion technologies, miniaturization of existing systems as well as innovative concepts have been proposed, however, very few were beyond Technical Readiness Level 3.
- Scaling down: Rose *et al.* (2012) argued that the real reason for little Smallsat applications is the lack of experience in Smallsat development of established aerospace corporations, which do not include Smallsats in their mission design trade. The authors attribute this to a lack of insight into mission design flexibility offered by application of Smallsats, the use of a whole infrastructure prepared for larger, conventional spacecraft, and the structure of cost models applied to the larger spacecraft-classes. In 5 to 10 years, it might be difficult to justify the use of expensive large spacecraft which mission could be attended by cheap, responsive Smallsats.
- Legal and regulatory issues: The Prague Declaration (ITU 2015) showed the need for adherence of Smallsat developers to international laws, regulations and procedures. These challenges include authorization, registration, frequency allocation, risk, liability, and insurance, as well as space debris mitigation (Marboe 2016). Shaw and Rosher (2016) summarize the international regulation and criticize the inappropriate registration procedures of the space industry, stating that registration of such space objects has in fact decreased. According to Trautinger (2016), the peculiarities of Smallsats provide a broad range of possible military and intelligence applications whose trade and transfer have to be limited and controlled for reasons of national and international peace and security. Due to military use of space there is a preoccupation that the huge amount of future Smallsats may put in risk the military satellites which are integrand part of nations defense systems.
- Space debris: more than 4,500 satellites have been launched since 1957. The intensive use of the space environment created more than 20,000 objects larger than 10 cm, 500,000 particles between 110 cm in diameter and about 10 million debris smaller than 1 cm (Gurfil and Seidelmann 2016). Space debris is considered as a serious problem for operational and future space missions. Active space debris capture and removal especially for non-cooperative targets is a demanding task for the future. The current status is reviewed by Shan *et al.* (2016).

SCENARIOS FOR SMALLSATS

According to the data presented in the previous sections and the future plans released by several organizations, it is clear that Smallsats have become real options in the space business. From that arises the questions of how big this market will become and when it is expected to happen. In order to address these questions, an analysis is conducted in this study to forecast possible scenarios for Mini-satellites, Micro-satellites, Nano-satellites and Pico-satellites.

Very few systems can grow exponentially for an infinite period. In the real world, there are negative feedback mechanisms that slow down the growth, leading to an upper limit, also known as carrying capacity. This systematic behavior can be represented by a sigmoidal-shaped logistic growth model in Eq. 1 (Meyer *et al.* 1999).

$$N(t) = \frac{\kappa}{1 + exp\left[-\frac{ln(81)}{\Delta t} \cdot (t - t_m)\right]} \quad (1)$$

The response $N(t)$ is the number of accumulated Smallsats per year. The logistic growth model is described by the 3 parameters κ, Δt, and t_m. The carrying capacity κ is the asymptotic limit that the growth curve approaches. The characteristic duration Δt specifies the required time to grow from 10 to 90% of κ. The parameter t_m specifies the midpoint, *i.e.* the time when 50% of the complete growth is reached (1/2 κ). The logistic growth model is symmetric around the midpoint t_m. After the phase of slowing down and saturation, there are 4 possibilities: (a) end of its life cycle; (b) stable rates with insignificant growth; (c) new growth process starts by some reason, *e.g.* by disruptive technology; (d) end of its life cycle, but with entry of a substitute. Systems with 2 growth phases can be approached with a bi-logistic model, using the sum of 2 discrete growth curves $N(t) = N_1(t) + N_2(t)$ (Meyer 1994).

The curve fit for the accumulative number of Mini-satellites launched between 1995 until 2014 is shown in Fig. 6. It is characterized by a sequential bi-logistic fit with 2 almost nonoverlapping curves. When the first pulse nearly reaches the saturation κ_1, the second pulse starts. The first pulse has Δt_1 = 2.8 years and its midpoint t_{m1} occurs in 1998 with a saturation of 108 Mini-satellites. This pulse seems to be

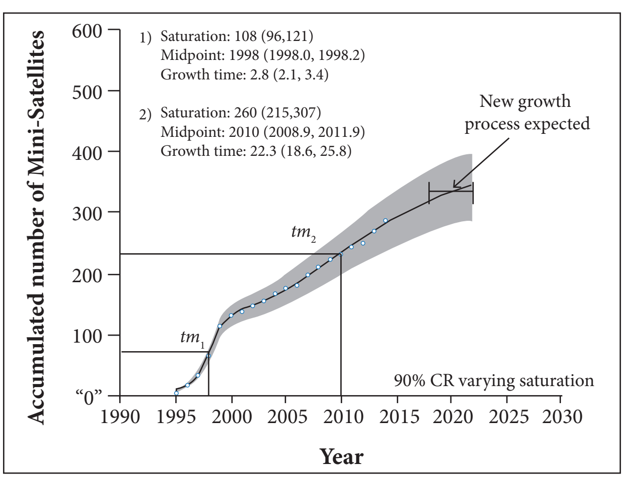

Figure 6. History and forecast of the number of accumulated mini-satellites (101 – 500 kg of wet mass) using a bi-logistic growth model. The black line is the model output, the white dots represent the input data (period between 1995 and 2014) and the gray region shows the range of curves with saturation values within 90% of confidence interval. The midpoints of the growth processes are given by t_m.

mainly induced by the Gonets and Globalstar constellations and the Kosmos satellites. Around 2000 comes the second pulse. It presents Δt_2 = 22.3 years, t_{m2} = 2010, and κ_2 = 260 Mini-satellites. It is induced mainly by international activities for individual satellites for remote sensing and scientific use, besides the upgrading of communication networks. If the Smallsat constellations mentioned in Table 2 become reality, a new growth process is expected to start around 2020.

Figure 7 reveals that the logistic curve fit for Micro-Satellites also shows a bi-logistic pattern. Unlike the Mini-satellites fit, the pulses are growing concurrently, leading to superposed curves. When the first pulse reaches about 50% of saturation, the second pulse starts growing. The first pulse has a Δt_1 of 3.7 years and a midpoint t_{m1} in 1998. Such characteristics is mainly caused by the deployment of the Orbcomm constellation. The second pulse has a Δt_2 of 19.8 years and a midpoint in 2008. This pulse is dominated by research and development, scientific and communication Smallsats. Between 2010 and 2013, the amount of launched Micro-satellites is inferior to the projection, whereas in 2014 it is superior. It seems likely that a tailback occurred, which was dispersed in 2014.

Micro-satellites do not have yet a standardization like the Cubesat-Standard, and budgets for satellites with test or development purpose are often limited and, in most cases, do not create launch demand. That might be the explain why the amount of launched Micro-satellites is inferior to the projection from 2010 till 2013. It seems likely that a tailback occurred that

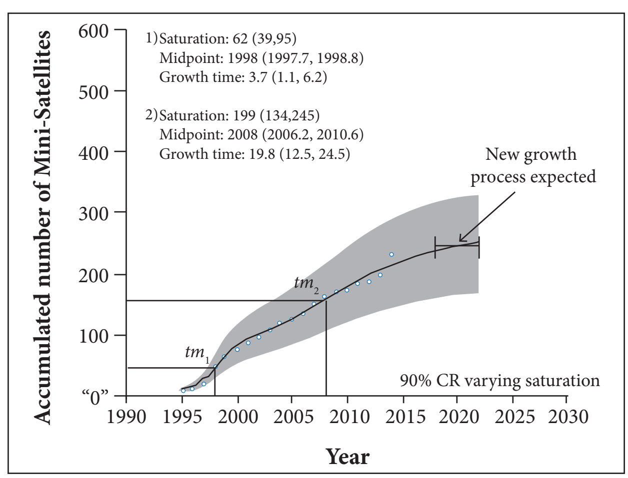

Figure 7. History and forecast of the number of accumulated micro-satellites (11 – 100 kg of wet mass) using a bi-logistic growth model. The black line is the model output, the white dots represent the input data (period between 1995 and 2014) and the gray region.

was dispersed in 2014 by a high amount of Micro-satellites launches. The saturation in Fig. 7 indicates 199 satellites; however, several new growth processes are expected to start towards the end of this decade caused by various planned constellations deployments (Table 2).

The findings for Mini- and Micro-satellites provide some evidence of a slowdown, with new growth pulses expected mainly induced by constellations. The Nano- and Pico-satellites though just start their process of growth, opening an important window of opportunities in this sector. The logistic fit for Nano and Pico-satellites in Fig. 8 projects a natural growth process with saturation of 2,043 satellites, Δt of 14.8 years with midpoint in 2020. This pulse seems to be characterized by international activities for individual satellites as well as distributed systems and constellations. Up to the year 2013, 1U Cubesats dominated the growth process. These are outnumbered by the emergence of a 3U Cubesat constellation in 2014, namely, Flock-1.

However, the prediction for Nano- and Pico-satellites has to be interpreted with caution, since the process of growth just started and there are many factors that could influence and change this projection. One of these factors is the availability of launch vehicles. The progress of the Small- and Micro-LV may influence the evolution of the Smallsat market. This market is looking for the emergence of launch vehicles with suitable payload mass and unit cost for dedicated launch of Mini- and Micro-satellites and cluster/rideshare of Nano- and Pico-satellites. In the following section, an assessment of the current and future launch vehicles is presented.

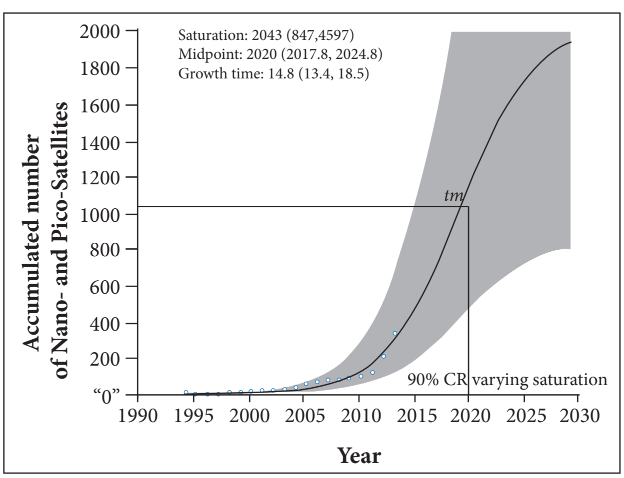

Figure 8. History and forecast of the number of accumulated nano- and pico-satellites (< 10 kg of wet mass) using a logistic growth model. The black line is the model output, the white dots represent the input data (period between 1995 and 2014) and the gray region shows the range of curve with saturation values within 90% of confidence interval. The midpoint of the growth process is given by tm.

LAUNCH VEHICLES FOR SMALLSATS

In order to launch the 863 Smallsats analyzed in the previous sections, more than 20 different launch vehicles were used (Fig. 9). These launch vehicles are classified by their payload capacities and according to Fig. 10, most launches were carried out by Medium-LVs, followed by Small-, Micro- and Heavy-LVs. The majority of Smallsats have been launched as piggyback (Heavy- and Medium-LV), rideshare (mostly Small-LV) or from ISS. Piggyback launch has the advantage of low price, but it implies a defined orbit, and eventually delays for the launch of the prime spacecraft. The availability of launch opportunities improved in the last years due to new secondary platforms, namely: ESPA (Atlas 5 and Delta 4) (Goodwin and Wegner 2001), ASAP (Ariane 5 and Soyuz) (Thiery 2008), VESPA (Vega) (Mowry

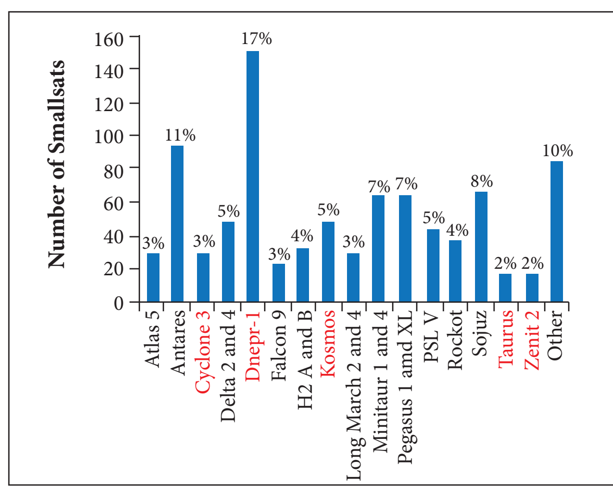

Figure 9. Launch vehicles of Smallsats that were launched between 1995 and 2014. The vehicles which launched less than 1% share of all Smallsats are not considered. The vehicles indicated in red are already retired.

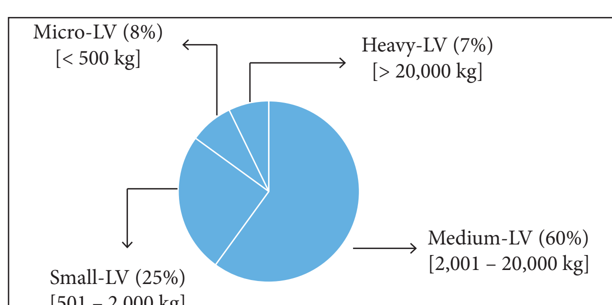

Figure 10. Share of launch vehicle class for launched Smallsats.

and Chartoire 2013) and SSPS (Falcon 9) (Anderson 2012). However, for Smallsats a considerable period of waiting time for launch is still common. Rideshare launch opportunities of Smallsats have similar disadvantages as piggyback, including the problem of common orbital parameters. Launching satellites from ISS, eventually available until 0 end-of-life of ISS in 2024, results in an elliptical orbit with an apogee of 380 – 420 km and inclination of 51.6°, with a satellite life expectancy of 100 – 250 days. Nanoracks, for example, had a backlog of 99 Cubesats awaiting launch from ISS in June 2015 (Foust 2015). Current and near-term launch manifest might not be appropriate for the planned commercial constellations identified in the 'SMALLSATS' section. The only commercially available Micro-LV appropriate for dedicated Mini- and Micro-satellites is Pegasus with a payload capacity of 250 – 310 kg. According to Table 3, it carries a price tag of USD 56.3 million. Moreover, a study conducted by Spaceworks Enterprises (Buchen and de Pasquale 2014) predicted for 2014 – 2016, that more than 50% of the 366 estimated Smallsats with wet mass of 1 – 50 kg will have commercial character, compared to only 13% in 2013. Apparently, this became true, since Doncaster *et al.* (2016) state that 37% of the satellites (< 50 kg) launched between 2009 and 2015 had commercial character. For the period of 2016 – 2018, a contribution of more than 70% commercial Smallsats is predicted. Euroconsult states that current offers of dedicated or shared launch for Smallsats are not satisfactory for operational missions such as Earth observation or telecommunications. Requirements for these missions include a reliable launch calendar and precise injection into orbit. Looking at this potential market, several countries and organizations have announced the development of Micro-LVs (Euroconsult 2015).

LAUNCH VEHICLES BY REGION

According to Fig. 11, around 85% of the LVs who carried Smallsats came from the US and Russia. It should be pointed out that most of the Russian launches carried non-Russian Smallsats and used decommissioned ICBMs, such as DNEPR, Kosmos and Rockot. Indeed, 38.1% of all Smallsats were launched from Russian LVs (Fig. 11), but only 11% were manufactured in Russia (Fig. 5). Besides US and Russia, several other countries are working on launch vehicles. In the following, an overview of the different launch vehicle developments is presented, which is summarized in Table 3.

Additional information on LVs can be found at the *International Reference Guide to Space Launch Systems* from AIAA (Isakowitz *et al.* 2004) and the Russian analog from Restart (Kobelev and Milovanow 2009).

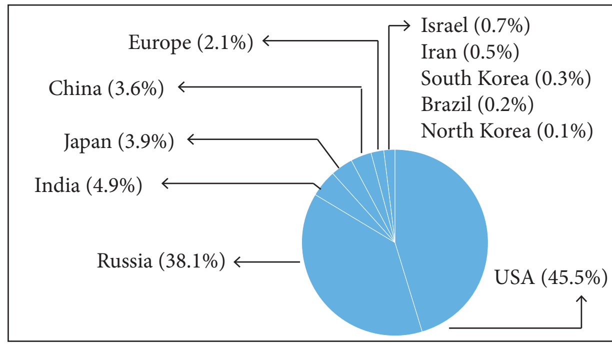

Figure 11. Share of Smallsats launched by country.

NORTH AMERICAN LAUNCH VEHICLES

Despite being responsible for about half of the Smallsat manufacturing and launches, the US has only one Micro-LV and no Small-LV commercially available. It is worth mentioning that Minotaur 1 and 4 LVs are not commercially available since they are powered by a mix of decommissioned government-furnished ballistic missile motors and commercial stages and subsequently they are only used for governmental missions. Consequently, most US Smallsats have been launched as secondary payloads. To address this market niche, there are several initiatives in the US, summarized in Table 3:

- In May 2015, NASA Launch Services Program issued a draft request for proposals for Venture Class Launch Services, in order to launch, before 2018, a total of 60 kg of Cubesats into LEO, on a single launch or divided into 2 launches.
- Firefly Space Systems is a new start-up that aims to develop an air breathing Micro-LV called Alpha. The payload capacity is 454 kg with a target launch price of USD 8 – 9 million. The first flight was expected for 2017 (Firefly Space Systems 2016); however, in October 2016, Firefly lost the backing of a major investor (Foust 2016).
- Microcosm disclosed the development of the Micro-LV Demi-Sprite. With a first launch date in 2017, it will be able to carry 160 kg of payload into LEO for USD 3.6 million (Sarzi-Amade *et al.* 2014; Microcosm 2016).

Table 3. Overview of commercially available Micro- and Small-LV in operation and in development.

		Launch vehicle (Organization,Country)	Number of launches/ reliability	Payload capacity [kg] (altitude × inclination)	Launch price (million USD)	Specific price [USD/kg]	First launch
Operational Launch Vehicle	Micro-LV	Pegasus XL (Orbital Science Corp., US) (OSC 2000)	42 / 93%	LEO: 310 (700 km × 70º) SSO: 210 (700 km × 98º)	56.3 (Killian 2014)	181,161–268,095	04/1990
	Small-LV	Epsilon (JAXA, Japan) (JAXA 2016)	1 / 100%	LEO: 700 (500 km × 30º) SSO: 450 (500 km × 98.6º)	47[1]	67,143–104,444	09/2013
		Long March-6 (CAST, China) (Spaceflight Now 2016)	1 / 100%	SSO 1,000	N/A	–	2015
		PSLV-XL[2] (ISRO, India) (Suresh 2009; SLR 2016)	35 / 94%	SSO: 1,750 (700 km × 98º)	25-35	14,285–20,000	09/1993
		Rokot (Eurockot, Europe and Russia) (Eurockot Launch Services GmbH 2011; Freeborn et al. 2000; Freeborn et al. 2005)	30 / 90%	LEO: 1,580–1,840 (700 km × 86.4º–63.2º) SSO: 1,350 (700 km × 98º)	30-35	16,304–25,926	12/1994
		Soyuz-2.1v (TsSKB, Russia) (Progress State Research and Production Space Centre 2016; Klyushnikov et al. 2014)	2 / 50%	LEO: 1,400–1,700	21	15,000–12,353	12/2013
		Vega (Arianespace, Europe) (Arianespace 2014)	7 / 100%	Polar: 1,430 (700 km × 90º) SSO: 1,330 (700 km × 98º)	35-45	24,476–33,834	02/2012
Launch vehicle in development	Micro-LV	Alpha (Firefly, US) (Firefly Space Systems 2016)	–	LEO: 454	8-9	19,868	2017
		Bloostar (Zero2Infinity, Spain) (Zero2Infinity 2016)	–	SSO: 75	4.5	60,000	2018
		Demi-Spite (Microcosm, US) (Sarzi-Amade et al. 2014)	–	LEO: 160	3.6	22,500	2017
		Electron (Rocket Lab, US and New Zealand) (Rocket Lab 2016)	–	LEO: 150	4.9	49,000	2017
		GOLauncher-2[3] (Generation Orbit, US) (Henry 2015)	–	LEO: 40	2,5	62,500	2017
		LauncherOne (Virgin Galactic, US) (Pomerantz et al. 2013; Henry 2016a)	–	LEO: 225	10	44,444	2017
		M-OV (Mishaal Aerospace, US) (Mishaal Aerospace 2016)	–	LEO: 363–454	N/A	–	N/A
		SOAR (Swiss Space Systems, Switzerland) (Werner 2015)	–	LEO 250	9.6	38,400	2018
		Super-Strypi[3] (University of Hawaii, Sandia and Aerojet, US) (ORS 2012; Clark 2015)	1 / 0%	Polar: 300	12-15	40,000–50,000	2015
		Tronador (CONAE, Argentina) (CONAE 2010)	–	LEO: 250	N/A	–	2019
		VLM-1 (AEB and DLR, Brazil and Germany) (Costa et al. 2012; Portal Brasil 2016)	–	LEO: 150	10	66,666	2018

...continue

Table 3. Continuation...

		Launch vehicle (Organization,Country)	Number of launches/ reliability	Payload capacity [kg] (altitude × inclination)	Launch price (million USD)	Specific price [USD/kg]	First launch
Launch vehicle in development	Small-LV	Athena-1c and Athena-2c[4] (Orbital ATK and Lockheed Martin, US) (ATK and Lockheed Martin 2012; Steele 2012)	–	LEO: 500 and 1,450 (700 km × 28.5°)	50 and 70	48,276–100,000	1995/2016
		Minotaur-C (Orbital ATK, US) (Orbital ATK 2014)	–	LEO: 1,350 (400 km × 28.5°) SSO: 1,000 (400 km × 98°)	N/A	–	2017

[1]Low-cost version of Epsilon for USD 30 million announced for 2017 Morita *et al.* (2012); [2]Other PSLV configurations: PSLV - LEO: 3200 kg, Polar: 1600 kg (622 km x 98°) and PSLV-CA - Polar: 1100 kg; [3]Planned first flight of suborbital GOLauncher-1 in 2017, PDR was realized in June 2016; GOLauncher-3 for 100 - 150 kg planned; [4]Retired from service in 2001; announced to be put back into production.

- Rocket Lab is developing the Electron Micro-LV aiming to deliver 150 kg into a 500-km sun-synchronous orbit. It will use a turbo-pumped liquid oxygen/kerosene engine, driven by electric motors. All primary components will be manufactured using 3-D printing. Commercial operations with a target price of USD 4.9 million are scheduled to begin early 2017 (Rocket Lab 2016).
- Generation Orbit in partnership with Space Propulsion Group won the first NEXT contract from NASA and they are developing the air-launched GOLauncher-2 (Henry 2015). The NEXT program (NASA Launch Services Enabling Exploration and Technology) is aimed at a dedicated Micro-LV, capable of placing 15 kg (3 × 3U Cubesats) into a 425-km orbit for USD 2.1 million by the end of 2017.
- Virgin Galactic is developing a liquid oxygen/kerosene engine for its LauncherOne Micro-LV. It is air-launched by a 747-400 dedicated carrier aircraft and has 300 kg of payload capacity into SSO and 450 kg into LEO. The price tag for launch is USD 10 million and initial orbital test flights are scheduled for late 2017 (Bergin 2016).
- Mishaal Aerospace intends to develop the M-OV Micro-LV to deploy 363 to 454 kg payload into LEO (Mishaal Aerospace 2016).
- The rail-launched Super Strypi, also known as SPARK, is a Micro-LV, based on the Strypi missile. With a price tag of USD 12-15 million, it is designed to launch payloads of up to 300 kg into high inclination LEOs. The first launch in November 2015 failed due to malfunction of the first stage motor and its future is unsure. The fact that it is based on military technology may limit its use to the US civil commercial market (ORS 2012).
- Orbital Science and ATK are using technology derived from Minotaur and Taurus launch vehicles to develop the commercial Small-LV Minotaur-C. A price tag was not released yet, but Minotaur-C will be capable of carrying between 900 and 1,500 kg into LEO and SSO. The first launch is planned for early 2017 (Orbital ATK 2014).
- LockheedMartin and ATK aremarketing the Athena Small-LVs to commercial and governmental customers. Athena- 2c launch carrying 1,700 kg payload cost about USD 70 million, whereas Athena-1c with 700 kg payload has a price tag of USD 50 million (ATK and Lockheed Martin 2012; Steele 2012). Athena-2c is using the rideshare concept to put 4-9 Smallsats with wet masses of 110 – 440 kg into orbit. Cubesats can also be launched at a price tag of USD 300,000.

As a final note for the US efforts, it should be mentioned that the Nanosat Launch Vehicle from Garvey Space Cooperation, Lynx Mark III from XCORS Aerospace and Neptune L-1000 from Interorbital Systems are not included herein because their focus is suborbital flights and/or no progress in recent years for a Micro-LV configuration could be found.

RUSSIAN LAUNCH VEHICLES

Russia has been responsible for launching 38% of all Smallsats from 1995 to 2014. The inclusion of Cyclone 3 and Zenit 2 as Russian launch vehicles follows the classification adopted by the database Futron Corporation (2013). Out of the 329 launched Smallsats, 213 were carried out by converted

ICBMs, namely DNEPR, Kosmos, Molniya, Rockot, Shtil, Start and Volna. This is a consequence of the Strategic Arms Reduction Treaty (START), an agreement between Russia and the United States, that defines the reduction of strategic offensive arms. The START treaty allows the conversion of these missiles into orbital launch vehicles (Anderson and Bonnema 2011). However, the converted missiles suffer from certain problems, like degradation, or they are simply sold out, and they will eventually be retired before 2020. The remaining 116 Smallsat deployments were conducted by Soyuz (65); Cyclone 3 (29); Zenit 2 (21); and Proton (1), which belong to the Medium- and Heavy-LV category.

There are no Russian announcements for the development of new Micro-LVs, but, in December 2013, the Small-LV Soyuz-2.1v had its maiden flight from Plesetsk Cosmodrome. Launch from the new Cosmodrome Vostochny is planned, and there are also considerations to launch from French Guiana. Soyuz-2.1v can deploy about 1,500 kg payload into LEO.

LAUNCH VEHICLES FROM OTHER COUNTRIES

The European launch vehicles currently available include Vega, Soyuz 2.1a and b and Ariane 5, Small-, Medium- and Heavy-LVs, respectively. Vega, the smallest one, has a payload capacity of about 1,430 kg into polar orbits. To fill the gap for very small payloads, the company Swiss Space Systems (S3) announced the intention to develop the Sub-Orbital Aircraft Reusable (SOAR). The concept foresees to launch a reusable suborbital spaceplane from an Airbus aircraft. The expendable upper stage separated from the reusable spaceplane will carry 250 kg payload, with first launch planned for 2018. The estimated development cost is USD 250 million. Zero2infinity is a high-altitude balloon company based in Spain that pretends to use a combination of balloon and rocket called Bloostar to deliver Smallsats of up to 75 kg into a 600 km SSO for USD 4.5 million.

India has used its Small-LV, the Polar Satellite Launch Vehicle (PSLV), to put 42 Smallsats into orbit. From those, only 9 Smallsats were Indian, the rest were manufactured by 15 different countries. Since PSLV has a payload capacity of about 1,750 kg, the majority of the Smallsats were launched as secondary payloads. Although eased at the end of 2012, Indian Space Research Organization (ISRO) is subject to ITAR restrictions.

In Japan, on the other hand, 31 out of 34 Smallsats were domestic payloads, launched by the Japanese M-V (3), H2A (28), H2B (3), Small-, Medium- and Heavy-LV, respectively. Japanese company IHI Aerospace developed a new Small-LV, Epsilon, capable of deploying up to 700 kg payload into LEO. The first flight occurred in September 2013. Despite being designed as a low-cost vehicle to substitute the M-V launch vehicle, the final launch cost was USD 47 million. JAXA has already announced a post-Epsilon development of a low-cost version in 2017 for USD 30 million.

In Asia, China is also working on the development and launch of Smallsats. In the period under analysis, 1995 – 2014, China has launched 31 Smallsats; 24 of them were manufactured on that country. Most of the Smallsats were launched by the Long March family, including Medium-LV 2C, 2D and Heavy-LV 4B and 4C. The Chinese have also tried to use the 4-stage all-solid propelled Micro-LV Kaituozhe 1, but the first two launches failed. Six foreign Smallsats, 3 Nano- and 3 Micro-satellites, were launched from 2012 – 2014. In order to gain more foreign launch contracts for Smallsats and to fill the gap in the Long March family, China is developing a new Small-LV. The Long March 6 with its new generation oxygen/kerosene engine has a payload capacity of approximately 1,000 kg into a 700-km sun-synchronous orbit. However, like India, China is also subject to ITAR restrictions.

Also on the Asian continent, North and South Korea have developed their Micro-LV, namely, Unha and NARO-1, respectively. Since they have military purposes, they are not considered as commercial options in the present paper. A similar situation occurs in the Middle East, where Iran and Israel have developed their own Micro-LVs Saphir and Shavit for military purposes.

In South America, Brazil and Argentina also have plans for developing Micro-LVs. As a matter of fact, Brazil has worked on its VLS-1 since the 1980s. VLS-1, an all-solid-propelled vehicle, has a payload capacity of 300 kg into LEO. After 2 launch failures, 1997 and 1999, and an accident on the launch pad in 2003, the program was canceled in 2016. A new development, the Micro-LV VLM-1, was initiated. This development is in cooperation with the German Aerospace Center (DLR) for exploration of launch services for Smallsats with a mass of up to 150 kg into LEO. The first launch is previewed for 2018 from Alcântara, a launch site located near the Equator. Besides equatorial orbits from Brazil, polar orbits are considered, launched from European launch sides. In the context of the Argentinian National Space Plan (CONAE 2010), Argentina has developed Smallsats, which have been launched by Russia, USA, India and China. There is also an ongoing program for the development of a Micro-LV, Tronador II. It aims at inserting 250 kg of payload into LEO, and its first launch is foreseen for 2019.

CHALLENGES TO OVERCOME

According to Fig. 10, only 8% of the Smallsats were launched by Micro-LVs. Therefore, the majority of Smallsats were launched as secondary payloads, which offers reasonable launch prices, but may not offer the desired launch date and orbit. To change this scenario, there are several initiatives for new Micro-LV under way (Table 3). To become successful, these initiatives will have to overcome, amongst other, the following challenges:

- Competitive price: the price tags of the Micro-LVs in development (Table 3) are all under USD 15 million. With the current technologies, these prices do not seem to be realistic. According to Hertzfeld (2013), the cost of getting into space has not changed significantly in the last half-century. About 70% of the total cost of a launch is the hardware, where motors and engines are the major cost components. Evaluating advanced launch concepts, Young and Mossman (2012) concluded that no alternatives for conventional concepts will be available in near future and air-launch and reusable LV are not a guarantee to save cost. Even by using conventional technologies, the Development; Qualification Flights; and Range and Ground Operations of these Micro-LV initiatives will require, besides a great infrastructure, a huge amount of financial resources. Therefore, unless substantial government funds are used to subsidize such initiatives, the commercial launch price might be much higher than those predicted in Table 3.
- Complexity: the operational launch vehicle market is dominated by well-established private and governmental organizations, which have appropriate infrastructure, capital, experience, know-how and well-established processes. However, according to Table 3, most of the organizations involved in the development of Micro-LVs are newcomers. Considering that the complexity of Micro-LVs is comparable to larger launch vehicles' and the current status of the projects, the previewed launch dates shown in Table 3 seem to be little realistic.
- Scaling down: similarly to the case of Smallsats, the business plans of established launch vehicle manufacturers are directed towards the development and production of huge launch vehicles. Scaling down might not be commercially desirable for these companies, since it will lead to profit reduction. This scenario may change, if major space agencies decide to provide reasonable resources for Micro-LV developments.
- Export control: developments in Argentina, Brazil and China may face export controls, not only for the launch vehicles itself, but also for the payload to be launched.

Some of these challenges have already led to the cancellation of various projects and programs, including:

- The European Aldebaran Launch Vehicle System Demonstrator was aborted in 2010. It was supposed to put 150 kg payload into SSO.
- The Nano-Satellite Launch Challenge from NASA was shut down in November 2012.
- Soldier-Warfighter Operationally Responsive Deployer for Space (SWORDS) was canceled in March 2014, which intended to deploy 25 kg payload into LEO for USD 1.5 million.
- The Airborne Launch Assist Space Access vehicle (ALASA) from the Tactical Technology Office of the US Defense Advanced Research Projects Agency (DARPA) was turned down after propellant problems in November 2015. ALASA was projected to launch 45 kg payload into LEO for less than USD 1 million.

CONCLUDING REMARKS

In this review, the past, the present and future trends of Smallsats and their launch vehicles have been analyzed. This analysis includes 863 Smallsats under 500 kg wet mass launched between 1995 and 2014, comprising about 1/3 of all satellites launched in that period. The United States were responsible for half of the Smallsat manufacturing business. Three different phases were identified: in the first phase (1995 – 2000) communication constellations were responsible for a peak of Smallsat launches (Orbcomm Micro-Satellites and Globalstar Mini-Satellites). During the second phase, from 2001 to 2012, a nearly constant number of about 30 Smallsats were launched per year. The third phase (2013 – 2014) was characterized by the launch of over 200 Nano-Satellites, being a direct result of the creation of the Cubesat standard in 2001. Such a boom of Nano-Satellites demonstrated new possibilities to the use of space-based technologies, awaking the interest of the space industry. This paper also identified the challenges involved in the development of Smallsats, including: Telemetry, Tracking and Command; Satellite propulsion; Scaling down; Competitiveness; and Legal and regulatory issues. Space debris is one of the most important factors, limiting the growth of the LEO Smallsat growth. Future scenarios for the different Smallsat categories have been proposed to address the questions of how big this market might become and when it is expected to happen.

The data analysis revealed that two third of the Smallsats launched between 1995 and 2014 used Medium- and Heavy-LVs, which offer reasonable launch prices, but may not offer the desired launch date and orbit. Therefore, most Smallsats flew as secondary payload. The United States responded for 45% of the market, being followed by Russia, which launched 38% of the Smallsats. Nonetheless, most of the Russian satellite launch vehicles were decommissioned ICBMs, which eventually will be discontinued until 2020. Despite the advantages of providing defined time schedule and orbital parameters, Micro-LVs (payload capacity under 500 kg) were only used for 8% of the Smallsats. As a matter of fact, there is only one Micro-LV commercially available today, but with a launch cost in the order of USD 50 million. It was concluded that the boom of Smallsats, brought about by miniaturization of electronics, was not followed by the decrease of the payload capacity of launch vehicles. Several initiatives around the world developing Micro-LVs have been identified, but it is uncertain if they will succeed as a viable commercial option, since most of their announced price tags seem unrealistic. Challenges to overcome include a competitive price, similar complexity as huge LVs, scaling down with profit reduction for LV manufacturers and export issues. Satellite launch vehicles, regardless of their sizes, have similar complexity and are inherently costly. Advanced launch concepts where not seen as realistic alternative in near and mid-terms. Unless substantial government funds are provided for Infrastructure; Development; Qualification Flights; and Range and Ground Operations, or some disruptive propulsion technology comes into place, it will not be feasible to build and launch competitive commercial Micro-LVs.

AUTHOR'S CONTRIBUTION

Wekerle T and Pessoa Filho JB co-wrote the main text; Costa LEVL worked on launch vehicle section; Trabasso LG conceived the idea of forecasting. All authors discussed the results and commented on the manuscript.

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