Nanosatellite missions — the future

O. Koudelka[1], R. Kuschnig[1], M. Wenger[1] and P. Romano[1]

1. Graz University of Technology, Institute of Communication Networks and Satellite Communications, Infeldgasse 12, 8010 Graz, Austria

In the beginning, nanosatellite projects were focused on educational aspects. In the meantime, the technology matured and now allows to test, demonstrate and validate new systems, operational procedures and services in space at low cost and within much shorter timescales than traditional space endeavors. The number of spacecraft developed and launched has been increasing exponentially in the last years. The constellation of BRITE nanosatellites is demonstrating impressively that demanding scientific requirements can be met with small, low-cost satellites. Industry and space agencies are now embracing small satellite technology. Particularly in the USA, companies have been established to provide commercial services based on CubeSats. The approach is in general different from traditional space projects with their strict product/quality assurance and documentation requirements. The paper gives an overview of nanosatellite missions in different areas of application. Based on lessons learnt from the BRITE mission and recent developments at TU Graz (in particular the implementation of the OPS-SAT nanosatellite for ESA), enhanced technical possibilities for a future astronomy mission after BRITE will be discussed. Powerful on-board computers will allow on-board data pre-processing. A state-of-the-art telemetry system with high data rates would facilitate interference-free operations and increase science data return.

1 Introduction

The concept of small and inexpensive satellites was introduced in 1999 by Prof. Bob Twiggs and Prof. Jordi Puig-Suari. The aim has been to allow students to be involved in all phases of a space project from design, implementation, testing, launch, operations and project management. The initial CubeSat standard defined a spacecraft with a size of 10×10×10 cm and a mass of 1 kg. Short development times and low cost made it possible that universities could realize such projects. CubeSats are co-passengers on a launcher with one or more main payloads, reducing the launch costs and making a mission affordable. Thus, CubeSat projects are ideal for education.

The first CubeSats have been launched in early 2000. By now around 500 small satellites were launched. In the last years an exponential increase in launches of CubeSats has occurred. A key success factor has been the introduction of standardized deployment mechanisms. This is a cassette with spring-load mechanisms, where the spacecraft is stowed inside the pod and secured by a spring-loaded door. When the release command is issued, a plastic thread holding the door in closed position is melted by an electric heater ('thermal knife'), the door opens and a spring pushes the satellite into space. Deployers such as the P-POD, the XPOD (by the Space Flight Laboratory of the University of Toronto), the ISIPOD or Nanoracks (which is a deployment mechanism on the International Space Station) with proven and well-established interfaces to a variety of launchers are commonly used.

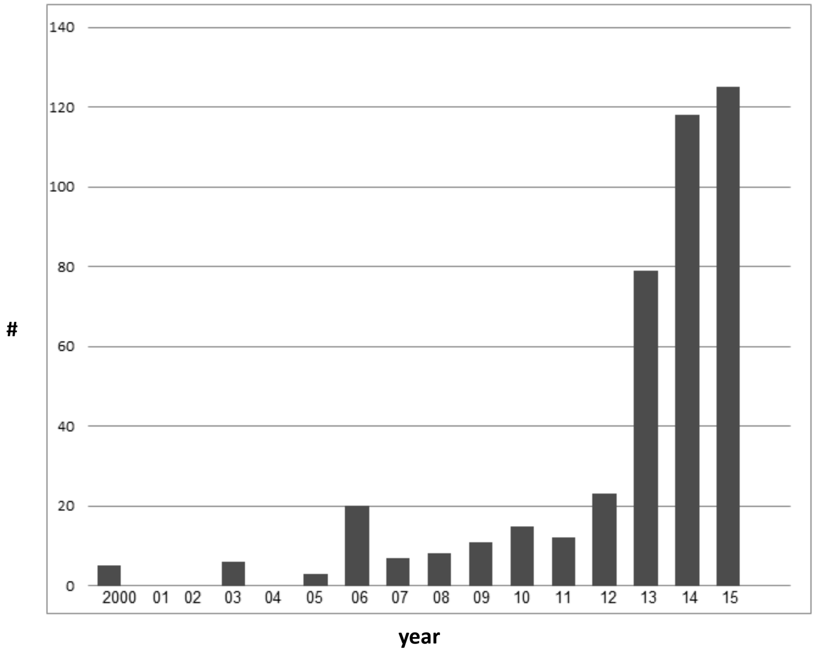

Fig. 1: Number of small satellites launched per year since 2000.

Initially, mostly 1 unit (1U) CubeSats with the original size of 10×10×10 cm were built and launched, followed by 2U and 3U CubeSats (10×10×30 cm). More recently, a trend to larger satellites (6U, 8U, 12U) can be observed. According to a common definition, all these satellites fall into the category of nanosatellites where the launch mass is between 1 and 10 kg.

2 Trends in small satellite missions

Figure 1 depicts the increase of launches of small satellites in the last years, clearly showing the significant increase of missions in the last three years (Swartwout, 2016). The distribution of organisations responsible for the missions in Fig. 2 exhibits an interesting trend (Swartwout, 2016). In the early years, most CubeSats were mainly built by universities, however now nearly two thirds of the spacecraft come from commercial entities, universities are responsible for 18.4 percent, governmental programs account for 12 percent and the military for 8 percent. This clearly shows that industry, research organisations and space agencies have adopted the technology for fast-track access to space, for validating and demonstrating new technology.

When evaluating the mission success rate, in the beginning only about 50 percent of small satellites achieved the mission goal. This can be attributed to the fact that less experienced student teams had to go through the learning curve. Another reason was that tests concentrated on unit level testing and dedicated insufficient effort on system level testing. However, the success rate has increased significantly due to the fact that commercial missions have been implemented and that space agencies,

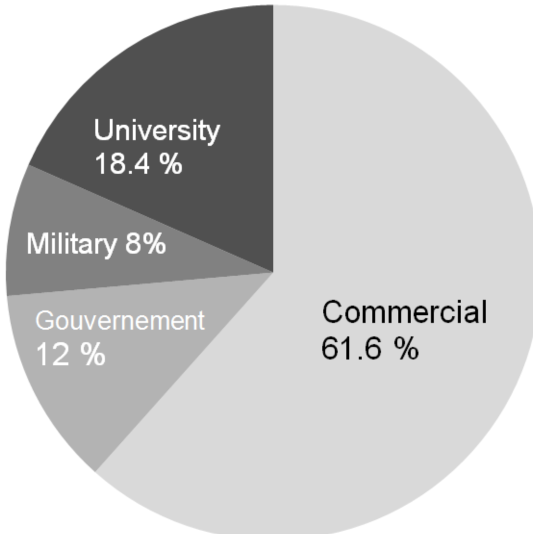

Fig. 2: Distribution of CubeSats by application.

industry and experienced research organisations became involved.

Quality/Product Assurance is vital in space missions. The ECSS (European Cooperation for Space Standardisation) standard has been developed over many years as applicable for space missions. It can be considered as a best practice tool. The ECSS standard was designed for large missions. Therefore applying it to nanosatellite projects would make them by far too expensive. The European Space Agency (ESA) has developed an ECSS standard tailored to small, fast-track missions. It is used e.g. in the OPS-SAT nanosatellite mission (Koudelka et al., 2015b).

Commercial companies such as Planet Labs or SPIRE using constellations of CubeSats for remote sensing or for improving maritime safety are taking an approach different from traditional space projects. One or only a few spacecraft undergo the full qualification and environmental tests, whereas the majority of the spacecraft are only functionally tested. Thus, a higher risk is taken. In case of failure, the non-functional spacecraft is simply replaced.

In the BRITE mission, no compromise on testing was taken. Environmental tests were conducted on unit and system levels. Thermal shock tests on all electronic boards, thermal vacuum, vibration, electromagnetic compatibility and open-field tests were carried out for the integrated spacecraft. 1000 hours of burn-in tests took place. This approach proved to be right. Although designed for a life-time of two years, the Austrian BRITE satellites (BRITE-Austria/TUGSAT-1 and UniBRITE) have been operating successfully for three years and eight months at the time of writing.

3 Examples of nanosatellite missions

Nanosatellites have been applied in a wide variety of missions, including

- Astrobiology
- Astronomy
- Atmospheric science
- Biology
- Pharmaceutical research
- Earth Observation
- Space weather
- Telecommunications
- Material Science
- Technology

BRITE is the world's first nanosatellite constellation dedicated to asteroseismology. NASA plans a constellation of formation-flying nanosatellites to create a virtual larger telescope. In the area of telecommunications, swarms of nanosatellites are already in use for monitoring of AIS (automatic identification system for ships) or ADS-B (automatic dependent surveillance – broadcast; for aircraft) signals. This helps to improve maritime and air traffic safety. Amateur radio payloads (beacons and transponders) still constitute an important fraction of nanosatellite payloads. A technology mission called OPS-SAT will be presented in Section 6.

4 Commercial systems

In the USA, start-up companies such as Planet Labs and SPIRE were created making extensive use of nanosatellites.

Planet Labs is currently deploying a constellation of up to 150 3U CubeSats for remote sensing services. Each CubeSat has a launch mass of 5 kg. Its payload is a camera with a 90 mm aperture. The ground resolution is reported to be around 6 m, which is less than that of large remote sensing satellites such as the Sentinels by ESA. An asset of SPIRE is the short revisit time due to the substantial number of satellites in the constellation.

SPIRE exploits CubeSat technology with a constellation of about 50 CubeSats with a 3U form factor. Fourteen LEMUR satellites are already in orbit. The applications of the SPIRE constellation is realized with an investment of 25 million $US. The applications are detection of AIS signals from space which allows identifying ships from space world-wide and GPS occultation. GPS occultation is a method using radio signals from the GPS navigation satellites. Signals reflected from the ground pass through the atmosphere and are picked up by low-orbiting satellites. When passing through the atmosphere refraction takes place, which is dependent on water vapour and temperature and can hence be used for weather forecasting and atmospheric research.

5 The BRITE science mission

The Bright Target Explorer (BRITE) constellation (Pablo et al., 2016) is composed of five nearly identical satellites, two from Austria, two from Poland and one from Canada. The satellites are described in other papers of these proceedings, therefore this section is kept brief. Each satellite carries a small telescope as scientific payload

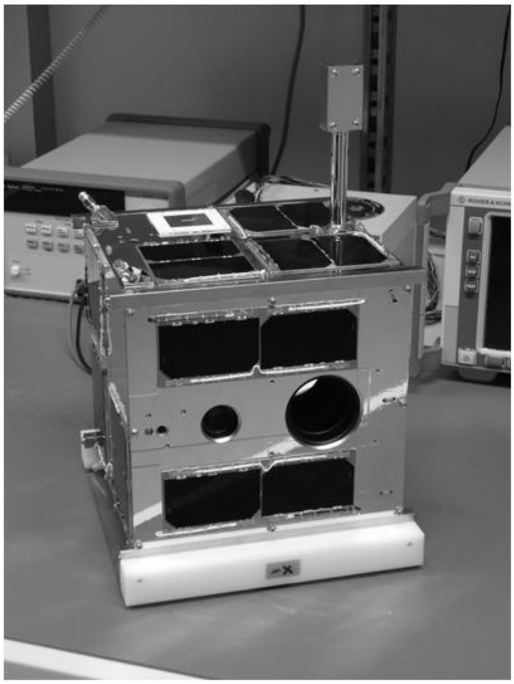

Fig. 3: BRITE-Austria satellite

which is used for photometry. The scientific goal of BRITE is the measurement of the brightness variation of luminous stars of magnitude +4. The attitude control system of the BRITE satellites provides a pointing accuracy of 1 arcminute which is remarkable for such a small spacecraft, but essential for the quality of the scientific data. Figure 3 shows the BRITE-Austria satellite during test in the clean room.

The BRITE satellites have been designed for a life-time of two years. The Austrian BRITEs which were launched in February 2013, and have now been in orbit for three years and eight months. It is projected that they can deliver science data with the required quality for at least two more years.

6 The OPS-SAT technology mission

OPS-SAT is the first ESA-owned CubeSat. The mission was initiated by the European Space Operations Centre (ESOC) with the goal to demonstrate and validate novel mission operations concepts and to carry out a variety of hardware and software experiments in space. Figure 4 shows the mock-up of the satellite. OPS-SAT is a triple CubeSat with deployable solar arrays and has a mass of about 6 kg. Figure 5 depicts the block diagram of the satellite. The left-hand part constitutes the robust satellite 'bus' (on-board computer with coarse ADCS system, GPS receiver, UHF back-up telemetry, power subsystem with deployable solar arrays and batteries), whereas the right-hand part contains the payload section. Part of the bus is the redundant FDIR (Fault Detection, Isolation and Recovery) module which monitors all payloads and controls the data and power buses. If a payload parameter (such as voltage, current,

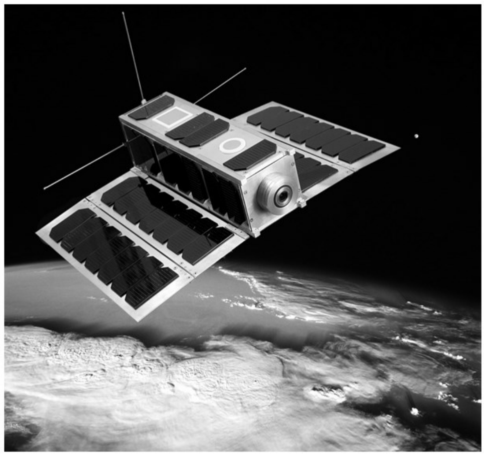

Fig. 4: OPS-SAT.

temperature etc.) is out of predefined limits, the FDIR computer will turn off the module to ensure satellite safety.

The S-band telemetry is fully compatible with the CCSDS standard, therefore OPS-SAT can be operated as any other ESA spacecraft. It is worth mentioning that OPS-SAT provides a telemetry uplink data rate of 256 kbit/s, the highest of any ESA spacecraft so far. This allows to upload complete on-board software images to the main processor payload in a fast way. In addition, an X-band downlink (at around 8 GHz) provides data rates up to 50 Mbit/s. The S-band transceiver and the X-band transmitter are developed by Syrlinks in France under CNES funding. The S-/X-band telemetry would be very suitable for a future astronomy mission which may require a high data return (Koudelka et al., 2015a).

The core payload is an ALTERA system-on-chip module with dual-core ARM-9 processors, a large field-programmable array and a solid-state mass memory of 16 GB. This processor payload operates nominally under a Linux operating system. The main software experiment is the demonstration of the new MO (Mission Operation Services) as a replacement of the Packet Utilisation Standard (PUS), which was introduced in the 1990s. An MO service is a set of operations which allow the exchange of data between a service consumer and a service provider.

The processing payload was successfully radiation tested at the ESTEC facility up to 20 krad. Such a payload would allow powerful data pre-processing on board the spacecraft and could be used in a follow-up astronomy mission (Koudelka et al., 2016).

A fine-pointing attitude control system is on-board which is a pre-requisite for optical communications and remote sensing experiments using a high-resolution camera.

A software-defined radio (SDR) payload allows radio signal and interference monitoring from space (this experiment was triggered by the interference issues experienced when the BRITE satellites pass over Northern Europe). The SDR module can oper-

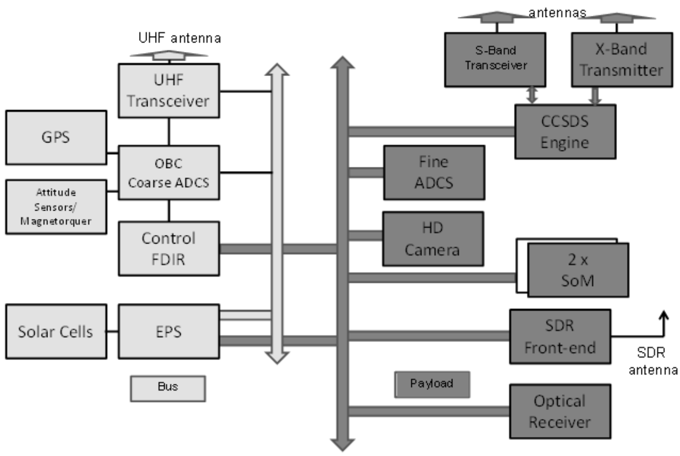

Fig. 5: OPS-SAT block diagram.

ate in the frequency range of 300 – 3800 MHz. On OPS-SAT, we will focus on the interference in the 70 cm amateur radio band.

A small optical receiver is on board which we will use for a free-space optics experiment. The laser station at the Lustbühel Observatory in Graz will uplink pulse-position modulated data. A single-photon counting device in the receiver in combination with the processing platform will facilitate the reception of cryptographic keys via the 16 kbit/s optical uplink. These keys, to be changed during every satellite pass over Graz, will be used to encrypt the radio downlink. The advantage of the optical transmission is that the signal is very difficult to intercept. To our knowledge, this is the first optical data transmission experiment to a CubeSat (Wittig & Koudelka, 2015).

7 Frequency coordination

Reliable communication systems are essential for any space mission. Traditionally, CubeSat missions have been using amateur radio frequencies in the VHF and UHF bands, to a lesser extent in the S-band. The advantage is that the frequencies are already pre-coordinated and hence the frequency coordination process is quite easy. Data rates are usually low (in the kbit/s range). BRITE utilizes the Science S-band on the downlink with a data rate of 32-256 kbit/s, whereas the uplink is operated in the 70 cm amateur radio band.

It shall be noted that the amateur UHF band is non-exclusive: the assignment is on a secondary basis only and no protection can be claimed. Interference on the uplink due to strong terrestrial radio sources present since October 2013 required a modification of the communication protocol for the BRITE telemetry to obtain a daily download volume of 18-20 Mbyte per day. Without interference the throughput could be twice as high. Future nanosatellite missions should therefore consider using

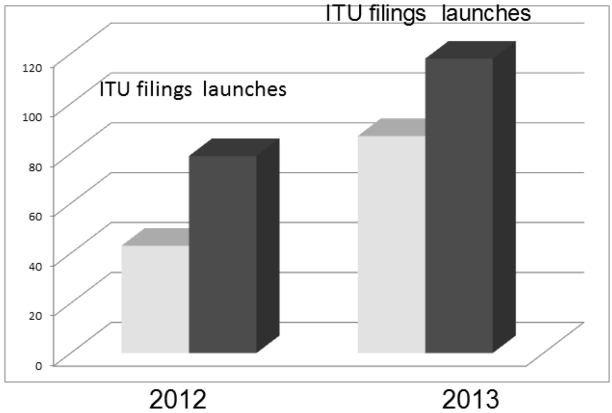

Fig. 6: ITU filings versus launches.

higher frequency bands (C-, X- or Ka-band), preferably in protected frequency bands.

International and national regulations require proper frequency coordination with the International Telecommunications Union ITU. The satellite owner or operator has to notify both IARU (International Amatuer Radio Union) and ITU, even if only amateur satellite service frequencies are used. Figure 6 shows the number of satellites launched and the ITU filings, exhibiting a clear mismatch. Apparently due to lack of knowledge or negligence a significant number of small satellite operators have not followed the mandatory process of frequency coordination. This is not only a breach of law, but also a risk of interference to other missions as well as their own.

8 Space debris issues

Since the beginning of the Space Age starting with the launch of Sputnik-1 in 1957 the amount of man-made objects in space (non-operational satellites, spent rocket upper stages, fragments of disintegration, etc.) has risen exponentially, increasing the risk of collisions. In 2007, China made an anti-satellite test, deliberately destroying a non-operational weather satellite of their own by a missile. This created a very high amount of space debris. Two years later, an operational IRIDIUM satellite collided with a defunct COSMOS satellite, again boosting the amount of space debris. The US Joint Space Operations Centre currently tracks about 18,000 man-made objects. The number of objects in the 1-10 cm range is estimated to be 670,000. When considering smaller objects the number is in the millions. Space debris has become a serious issue. The UN Office for Outer Space Affairs dedicates significant effort to arrive at international agreements to reduce space debris. It shall be mentioned that we receive typically every three to four weeks a conjunction warning for BRITE-Austria and UniBRITE.

The Inter-Agency Space Debris Co-ordination Committee formulated a Code of Conduct stating that a space object should not stay in orbit for more than 25 years after the end of the mission. This can be accommodated by choosing the orbit such that the decay and final burn in the lower atmosphere happens within this time-frame.

In order to achieve this de-orbit requirement, for a typical CubeSat the orbital height should be below 620 km. Other possibilities include the use of small thrusters (e.g. micro arc-jets) on board for lowering the orbit or the increase of the ballistic coefficient by deploying structures (e.g. sails).

9 Summary

Nanosatellites and CubeSats have matured from pure educational projects to in-orbit demonstrators and technological proofs of concept. Industry and space agencies are increasingly using nanosatellite technology. Commercial services in the field of remote sensing and monitoring of maritime signals are already in place using constellations of CubeSats. The reliability of these small satellites has increased due to professional implementations. The BRITE mission impressively demonstrates that demanding scientific objectives can be met with inexpensive spacecraft. The pointing accuracy and the quality of the scientific instrument are better than the original specification. The Austrian BRITE satellites are now in orbit for nearly twice the specified operational period of two years. Assessment of the performance suggest that the mission can be extended for at least two more years.

Telemetry systems compliant with the CCSDS standard, operated in protected bands are recommended for future nanosatellite missions. Powerful processors as developed for the OPS-SAT satellite will allow advanced on-board data pre-processing for follow-on missions of BRITE.

The exponential increase in deployed small satellites requires strict adherence to existing rules and procedures to avoid harmful interference and space-debris problems.

Acknowledgements. Based on data collected by the BRITE Constellation satellite mission, designed, built, launched, operated and supported by the Austrian Research Promotion Agency (FFG), the University of Vienna, the Technical University of Graz, the Canadian Space Agency (CSA), the University of Toronto Institute for Aerospace Studies (UTIAS), the Foundation for Polish Science & Technology (FNiTP MNiSW), and National Science Centre (NCN). The OPS-SAT nanosatellite is funded by the ESA GSTP program. The authors wish to thank the colleagues of the Spaceflight Lab of the University of Toronto, in particular Dr. Rob Zee and Mr.Cordell Grant for the excellent cooperation in the BRITE mission.

References

Koudelka, O., Wittig, M., Evans, D., *Advanced Processing and Communications Payloads for Nanosatellite Missions*, *Proc. IAC 2015, B2.4.4* 3531 (2015a)

Koudelka, O., et al., *ESA's OPS-SAT Nanosatellite Mission — A Laboratory in the Sky*, in IAA Small Satellite Symposium, 1–8, IAA (2015b)

Koudelka, O., et al., *Small Satellites for Telecommunications and Science Missions*, *Proc. IAC 2016, B2.5.4* 3097 (2016)

Pablo, H., et al., *The BRITE Constellation Nanosatellite Mission: Testing, Commissioning, and Operations*, PASP **128**, 12, 125001 (2016)

Swartwout, M., *CubeSat Database* (2016), URL `http://sites.google.com/a/slu.edu/swartwout/home/cubesat-database`

Wittig, M., Koudelka, O., *Telecommunications Missions Based on Nanosatellites*, *Proc. IAC 2015, B2.4.4* 3517 (2015)

Fig. 7: Otto Koudelka, Werner and Waltraud Weiss