Doing Science with Nano-Satellites

Anna Gregorio, Alessandro Cuttin, Mario Fragiacomo and Mauro Messerotti

Abstract Nano-satellites represent a new generation of satellite platforms that is opening its own market niche expanding extremely quickly. These satellites are small and light, thanks to their cubic shape they are also modular and have raised the interest of space operators thanks to their jack-in-the-box concept. Particularly interesting is the Earth Observation and remote sensing segment, that has large potential applications for safety issues, or even more practical applications for agriculture. The possibility of using a constellation or a network of nano-satellites as a new generation of telecommunication (e.g. for mobile applications) or navigation systems seems also very appealing for the next future. Besides the advantages of using nano-satellites, this type of space missions still presents a number of technical issues; one of these is the on-board telecommunication system that, working at low frequencies, provides a very limited data rate preventing the transmission of large amounts of data. Only by improving this system, nano-satellites can become real science space missions.

Keywords Nano-satellites · Earth Observation · Remote Sensing · Telecommunication system · Constellation of satellites

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1 Introduction

Nano satellites represent a new generation of satellite platforms that is opening its own niche, expanding extremely quickly. These satellites are very small, light, and thanks to their cubic shape they are also modular, as Lego® bricks, and have raised the interest of space operators thanks to their jack-in-the-box concept. Born as educational tools, nano-satellites are now becoming real scientific and technological space system, although a number of issues still needs to be solved.

In this paper we want to briefly analyse the status and future of science missions nano-satellites. After a brief introduction on nano-satellites and what has already been achieved with these missions, we will focus on the most significant science topic in this field, Remote Sensing and Earth Observations. Remarks on some technical issues are also given; finally we give some conclusions.

2 Science with Nano-satellites

2.1 Nano-satellites

From the late 90s, with the construction of the first small satellites with very compact mass and size, space technology, an almost exclusive prerogative of large companies specialised in the aerospace field, wants to become a technology available to small companies, facilities and research institutes, historically smaller in terms of personnel and less funded. The design can be complex, given the environment in which such systems have to operate, but it is clear that the so called "CubeSat" systems, initially designed for educational purposes, are being brought to the daily technological and scientific use (Hevner et al. 2011). Over the last decade more than one hundred CubeSats, modular small satellites whose basic element is an Aluminium cubic structure of 10 cm side, have been launched. This number will double very soon and in recent years interest for small satellites has grown considerably also for commercial applications further expanding the potential of these systems.

In recent years the nano-satellite concept of a cubic satellite for educational purposes has evolved and now belongs to a wider class of satellites, building satellites using CubeSat bricks using up to 27 units ($3 \times 3 \times 3$) which provides for the extension of the satellite to larger boxes with mass up to 50 (The CubeSat Program 2014).

A recent study by SpaceWorks Enterprises, one of the world leaders in satellite launch field, presented a comprehensive analysis of trends of small satellites, in the class 1–50 kg. Spaceworks projections, see Fig. 1, based on announced and future

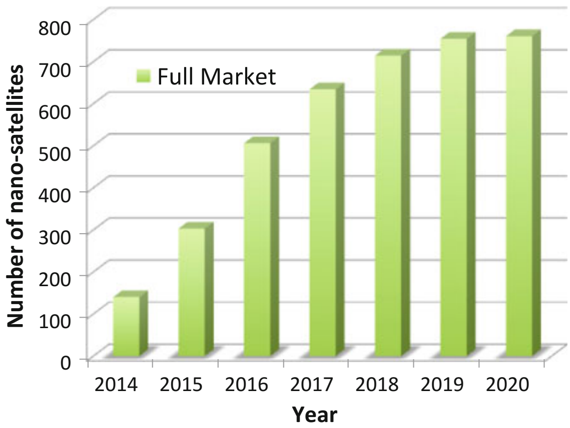

Fig. 1 Number of past and future launches according to SpaceWorks analysis

plans of developers and programs indicate as many as 3000 small satellites to be launched from 2016 through 2022.[1]

According to these projections, applications are diversifying with increased use in the future of Earth Observation and remote sensing missions from less than 40% of the total number of nano-satellites towards almost 75%.

What is not specified in this study is the interest demonstrated by the International Science Community in the space field towards the usage of these platforms for small science missions. Just as one of the most important facts in 2016, in January the International Space Science Institutes in Bern, Switzerland, organized a Forum during which international researchers with active experiences in CubeSats and their development discussed on three major topics:

- Identify suitable CubeSat missions, discuss their feasibility and/or science results already been achieved;
- Identify barriers that limit the science impact of the CubeSat platforms;
- Characterize limitations of a CubeSat platform for science purposes.

One of the results on this forum was the creation of a short internationally focused consensus document, “white paper”, summarizing the status of small space missions and the way to go forward, that is being prepared.

Particularly interesting are the Earth Observation and remote sensing fields, with a number of potential applications ranging from safety issues (e.g. water and fire monitoring), to more practical applications for agriculture.

Although it is evident that Remote Sensing and Earth Observations represent the main Science field for small space missions, it is worth mentioning the impressive number of science topics that is being touched by CubeSats with at least one representative mission example:

[1]SpaceWorks Nano Microsatellite Market Forecast http://spaceworksforecast.com/2016-market-forecast/.

- Spaceweather, Meteorology, Atmospheric and Solar Physics: DICE, FireFly, GRIFEX (GEOCAPE ROIC In-Flight Experiment) (Robinson and Moretto 2008; Crowley et al. 2011);
- Astronomy, Astrophysics, Particle and Nuclear Physics: Astro-1, ELFIN (Electron Losses and Fields Investigation), CuSPP (CubeSat mission to study Solar Particles over the Earth's Poles)[2];
- Lunar, Interplanetary and Asteroid missions: Lunar Flashlight, Near Earth Asteroid (NEA) Scout, SIMPLEX, INSPIRE (Interplanetary NanoSpacecraft Pathfinder In a Relevant Environment) (Spangelo et al. 2015);
- Interferometry and Constellation: EDSN (Edison Demonstration of Smallsat Networks)[3];
- Space Debris (Clean Space One, D-Orbit)[4];
- Biology and Human Health: BioSentinel[5];
- Navigation and Telecommunication systems: PhoneSat, ISARA (Integrated Solar Array and Reflectarray Antenna), OCSD (Optical Communications and Sensor Demonstration).[6]

Correspondingly new instrumentation is being miniaturized and can eventually be used as an important test bench for future larger missions:

- Electric and magnetic field instruments, plasma density and temperature instruments, neutral gas pressure gages and wind instruments, mass spectrometers;
- Particle detectors, Gamma and X ray detectors, photometers and spectrometers, hyper-spectral imagers;
- Advanced radio receivers (GNSS receivers, microwave radiometers).

2.2 Remote Sensing and Earth Observations

Earth Observation from satellites allows the acquisition of global and synoptic detailed information about the planets (including the Earth) and their environments. Sensors on Earth-orbiting satellites provide information about global patterns and dynamics of clouds, surface vegetation cover and its seasonal variations, surface morphologic structures, ocean surface temperature, and near-surface wind. The rapid wide coverage capability of satellite platforms allows monitoring of rapidly changing phenomena, particularly in the atmosphere.

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[2] https://www.nasa.gov/content/goddard/nasas-science-mission-directorate-cubesat-initiative.

[3] https://www.nasa.gov/directorates/spacetech/small_spacecraft/edsn.html.

[4] http://www.deorbitaldevices.com/.

[5] https://www.nasa.gov/centers/ames/engineering/projects/biosentinel.html.

[6] https://www.nasa.gov/directorates/spacetech/small_spacecraft/isara_project.html, https://www.nasa.gov/directorates/spacetech/small_spacecraft/ocsd_project.html.

Remote sensing can significantly contribute to provide a timely and accurate picture of the agricultural sector, as it is very suitable for gathering information over large areas with high revisit frequency. A close monitoring of agricultural production systems is necessary, as agriculture shall strongly increase its production for feeding the nine-billion people predicted by mid-century. This increase in production must be achieved while minimizing the environmental impact of agriculture. Achieving this goal is difficult, as agriculture must cope with climate change and compete with land users not involved in food production (e.g., biofuel production, urban expansion, etc.). The necessary changes and transitions have to be monitored closely to provide decision makers with feedback on their policies and investments. Nano-satellites is already being used in this field (Kramer and Cracknell 2008), instruments like the TMA (Three Mirror Anastigmat) telescope, on board the Proba-V (Francois et al. 2014), a small ESA (European Space Agency) mission for Vegetation studies, is now being miniaturized and brought to CubeSats.

It is worth mentioning that in this context the University of Trieste, with the two departments of Physics and Engineering and Architecture, is developing a new low cost detector, named PicoAgri, dedicated to agriculture monitoring to be used on board nano-satellites. The detection system is made of an optical system and a sensor, the processing unit used by now is by now an Arduino 1, that have been already demonstrated to work in flight although we are analysing the possibility of using a more powerful unit. The system is mostly based on COTS (Commercial Off The Shelf) devices that are being adapted to the requirements of the system. The acquisition of the satellite image is performed via a *multispectral sensor* that cover four spectral bands simultaneously, blue (459–479 nm), red (620–670 nm), near Infrared (841–875 nm) and shortwave infrared (1628–1652 nm). PicoAgri uses four different sensors, one for each spectral band, to reconstruct the spectral image of the soil; the satellite acts as an *along track scanner* (*push-broom scanner*) to obtain the spectroscopic image. The camera consists of an optical system projecting an image onto a linear array of sensors, the CCD array, arranged perpendicular to the flight direction of the spacecraft. We analysed possible COTS components both for the sensor and optical systems; linear CCD systems have been identified, acquired and are now being tested while suitable lenses are not available on the market. A dedicated optical system is in the design phase. The principal advantage of this type of sensor is the lack of mechanical parts, this prevents malfunction and extend the satellite lifetime.

3 Technology Issues

Besides the many advantages of using nano-satellites (cost and time effectiveness, focused objectives, fast turn-around experimental approaches), with respect to large missions nano-satellites intrinsically hold some limitations, mostly related to their physical size, and as a consequence on power and attitude control systems. In addition, nano-satellites still present a few technical issues; one of these is the on-board telecommunication system that, working in the low frequency radio-amateur band, provides a very limited data rate preventing the transmission of large amounts of data.

In particular Earth Observation and remote sensing space missions produce large amounts of data that directly reflect the quality of scientific data (i.e. image resolution) they produce. For this reason these applications are accessible by now only by larger satellites providing high data transmission rate. Only by improving the telecommunication system of small satellites thus enabling the transmission of large amount of data, nano-satellites can become real science space missions. In this context, the University of Trieste with its recently born spin-off company PicoSaTs, envisages a new generation of nano-satellite communication systems working at high frequencies (Ka band) providing very high data rates.

The constantly growing number of orbiting nanosatellites is not yet followed by an improvement in the communication technology they use, with the obvious exception of those spacecrafts that are launched by companies that have demanding payloads, and address this issue with proprietary solutions. To date, most orbiting CubeSats mount wire antennas and use frequencies allocated in the radio amateur service (Klofas and Leveque 2012).

We assume that the main reason behind this technological gap is that the majority of the organizations face a space mission for the first time, and therefore prefer to use devices that are proven to be reliable.

To satisfy the need for more downloaded data keeping the existing technology, ground station replication is a viable option. Increasing the contact time with a number of known ground station increases the capability of downloading more data in a linear fashion. Some initiatives address this approach with different levels of success (Leveque et al. 2007; Pandolfi et al. 2016; White et al. 2015).

Another option to sustain a demanding data budget is to address the technological issues of providing nanosatellites with the capabilities of using communication systems at higher frequencies, like those in the Ka band. Corresponding wavelengths enable the design of small and directive antennas, and, as a consequence, faster data rates can be obtained.

The importance of equipping CubeSat with performing radios is also enabled by the presence on the market of ADCS with sufficient capabilities to ensure the proper pointing of highly directive antennas. The result of the optimized radiation pattern of the antenna array is shown in Fig. 2.

A proposed solution (Cuttin et al. 2015) consists of an array of microstrip patches, a convenient approach in terms of size, mass, mounting and cost. Otherwise, efficient radiators such as parabolic reflectors, horn antennas, and reflect arrays have demanding requirements in terms of mass or volume requirements (King et al. 2012; Hodges et al. 2013; Sauder et al. 2015).

Thanks to an advantageous algorithm capable of optimizing the far-field of arrays by means of the definition of proper masks (Buttazzoni and Vescovo 2014), as shown in Fig. 2, it has been proved that a small but directive antenna, consisting of a circularly polarized array of 256 patch elements tuned at 37 GHz, can be housed on one face of a CubeSat.

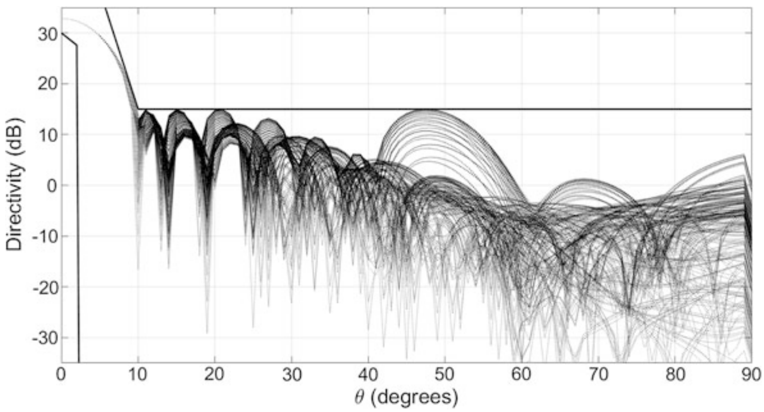

Fig. 2 Optimized radiation pattern of the antenna array

Such antenna could easily be used to perform data downlink at a very fast data rate.

4 Conclusions

In recent years the nano-satellite concept has evolved and now belongs to a wider class of satellites with mass up to 50 that is being brought to the daily technological and scientific use.

With respect to larger satellites, these nano-satellites are agile, meaning cost and time effective, they can focus on specific scientific objectives and, being based on a standard platform, provide a fast turn-around experimental approach mitigating also issues related to measure gaps. Besides that, they still represent an important educational tool that allows creative mission ideas to reach a successful implementation, thus enhancing university participation in space activities, eventually training the next generation of scientists and engineers in space by offering full end-to-end mission experience.

From the scientific and technological point of view, nano-satellites represent a potential tool for advanced research in many science areas. They already demonstrated the capability to cover an impressive number of science topics, ranging from spaceweather, atmospheric and solar physics, astrophysics and particle physics or even dedicated to biology and human health, to sophisticated lunar and interplanetary missions, or even more technological missions for navigation and telecommunication or based on interferometry and constellations.

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