Applications of Nano-Satellites and Cube-Satellites in Microwave and RF Domain

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Abstract

This paper presents an overview of microwave technologies for Small Satellites including NanoSats and CubeSats. In addition, examples of space communication technology demonstration projects using CubeSats are presented. Furthermore, examples of miniature instruments for Earth science measurements are discussed.

1.0   Introduction

The history of modern day satellite communications can be traced back to the development of small satellites in the 1960s, with the goal of providing over-the-horizon long-distance telephone service. Explorer-I was the first American satellite that was successfully launched into space on January 31, 1958. The satellite weighed less than 14 kg, of which, 8.4 kg was instrumentation to detect cosmic rays and micrometeorite impact, and sensors for temperature measurement. The Explorer-I was the first of a series of satellites of that era. The size and mass of these satellites were primarily limited by the capabilities of the launch vehicles of that period. As the launch vehicle capabilities advanced, so did the mass and data throughput of the satellites, which are currently on the order of several 1000 kg and over 100 Gbps. Over the past half a century, the improvements in spacecraft technology have been primarily in the areas of microelectronics for on-board processing, high frequency electron devices, and integrated circuits for communications and navigation, solar cells and batteries for on-board power generation and storage, thruster technologies for propulsion and orbit determination, micromechanical systems (MEMS) and optoelectronic/optical devices for sensors and instruments, etc. Hence, the term small satellite is not revolutionary but merely indicates the progression in technological innovations that has taken place, which has enabled satellite manufacturers to package a wide range of functionality into a small volume at an affordable cost and shorter development time. The efficiencies gained have enabled satellite developers to place useful payloads into small satellites without degrading performance and capability, which was previously possible with only very large satellites.

To cater to a diverse range of missions, the small satellites community has adopted granularity in the overall mass as a basis for defining the mission class. Table I presents these definitions. Among these, the Nanosat has drawn tremendous interest in recent years, because it enables easy and cost effective options, even for small companies and universities, to provide hand-on experience in building a spacecraft and later deploying it in space. The deployment is by sharing the ride to space as a secondary payload, by using the available excess margin, after the integration of the primary payload on to a launch vehicle. Thus the major benefit is the significantly lower cost to develop and deploy a Nanosat compared to a conventional large satellite.

To facilitate the above goals of providing low cost access to satellites, the community has further adopted a standard, which is dubbed as CubeSat. Prof. R.J. Twiggs at the Stanford University pioneered the development of CubeSats (Ref. 1). A CubeSat measures 10 cm on a side, weighs about a kg, and is assembled using commercial-off-the-shelf (COTS) components. This form factor is defined as "1U" unit. A single CubeSat could either serve as a standalone satellite with limited functionality or serve as a building block for a larger Nanosat or a Microsat. For example, a "3U" Nanosat will consist of three CubeSats. Thus, the major advantage of this standardization is that launch vehicle manufacturers, regardless of who built the CubeSats, can adopt a common deployment system. Prof. J. Puig-Suari at the California Polytechnic State University developed such a standard deployment system. This system is known as the Poly Picosatellite Orbital Deployer (P-POD) (Ref. 1). This deployment system can accommodate multiple Nanosats with a range of form factors, which allows spreading the launch cost across several customers, resulting in lower launch cost per customer. Applications of Nanosats include, communications, remote sensing, scientific research, high-resolution still imagery, maritime applications such as ship tracking, formation flying to create large synthetic aperture for imaging radar, etc.

TABLE I.—SMALL SATELLITE NOMENCLATURE

Generic name	Launch weight[a]
Smallsat	100 to 500 kg (220 to 1100 lb)
Microsat	10 to 100 kg (22 to 220 lb)
Nanosat	1 to 10 kg (2.2 to 22 lb)
Picosat	0.1 to 1 kg (0.22 to 2.2 lb)

[a]Wet mass with fuel at launch

2.0 Challenges Facing the Small Satellite Industry

The first and foremost challenge for the small satellites is the radio spectrum. The uplink and downlink frequencies for CubeSats are typically in the UHF band (435 to 438 MHz), which are regulated by the International Amateur Radio Union (IARU). At UHF the available bandwidths are very small and so are the achievable data rates. Hence, there is a push to migrate into the higher X-band and Ka-band frequencies, were the available bandwidths are larger. However, this requires special license to deploy and operate.

The second challenge for small satellites is the sustainability of the business in the case of small start-up companies. An area that has drawn a lot of interest in using small satellites is remote sensing of the Earth from space. These service providers propose using a constellation of small satellites that are capable of delivering global high-resolution scientific grade Earth multispectral imagery on a daily basis. Applications may include both commercial and military. Potential applications may include agriculture yield, oil and natural gas exploration and production, deforestation, mapping and geospatial services, tracking of ships in seas, emergency response, national security, mobile device support, etc.

The next challenge for small satellites is the cleanup and removal of space debris. Thus, small satellite manufactures will need to develop an innovative mechanism to deorbit at the completion of their mission.

Finally an additional challenge for small satellites, is finding the appropriate launch opportunity with affordable cost. This issue has been partly addressed by sharing the ride as a secondary payload, on a launch vehicle equipped with a P-POD system.

3.0 CubeSat Architecture

The CubeSat architecture is modular and each subsystem resides on a separate printed circuit board. The subsystems include the communications subsystem (CS), the on-board controller (OC), the attitude determination and control (ADC) subsystem, the electronic power supply (EPS), and the payload. The OC routes the data from the payload to the CS and operates the radio in the CS. In addition, it processes the data from the ADC, controls the EPS, and facilitates communications between the various subsystems through the satellite bus. A simplified block schematic of the CubeSat architecture is presented in Figure 1.
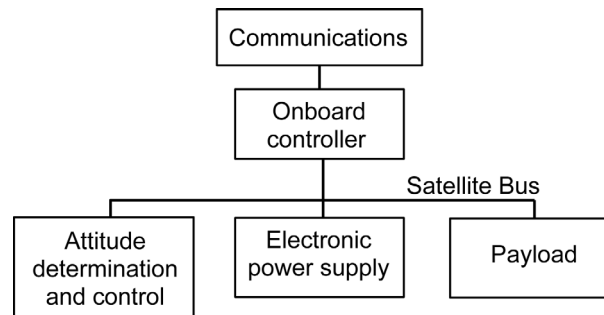

Figure 1.—A simplified block schematic of CubeSat architecture.

4.0 CUBESAT Communications Subsystem

The communications subsystem not only supports the transmission of the data from the payload to the ground station but is also responsible for the tracking, telemetry, and command functions. The communications subsystem consists of the radio and the antenna. The radio includes the transceiver, the low noise amplifier (LNA), the high power amplifier (HPA), and the diplexers. A simplified block schematic of the communication subsystem is presented in Figure 2.

4.1 Antenna

The CubeSat antenna must have an omnidirectional radiation pattern to communicate with Earth terminals located at any latitude. A second requirement is that the antenna must be capable of being stowed during launch and later deployable on-orbit. To meet these requirements a deployable turnstile antenna is recommended. The turnstile antenna consists of four monopole antennas located at the four corners of either the top or bottom panel of the CubeSat and properly phased so as to generate a circularly polarized (CP) omnidirectional radiation pattern.

4.2 Transceiver

The transceivers are commercially available from several vendors and operate in a half-duplex mode. They are configured to transmit and receive data at rates ranging from 1.2 kbps up to 9.6 kbps using a variety of modulation schemes including FSK, GMSK, and GFSK, etc. They are also capable of implementing both forward error correction (FEC) and Viterbi coding. The typical operating frequencies have been in the UHF band. However, in some instances, CubSats have operated in the Industrial Scientific and Medical (ISM) band (2.4 GHz) and in the Space Research band (2.2 to 2.29 GHz).
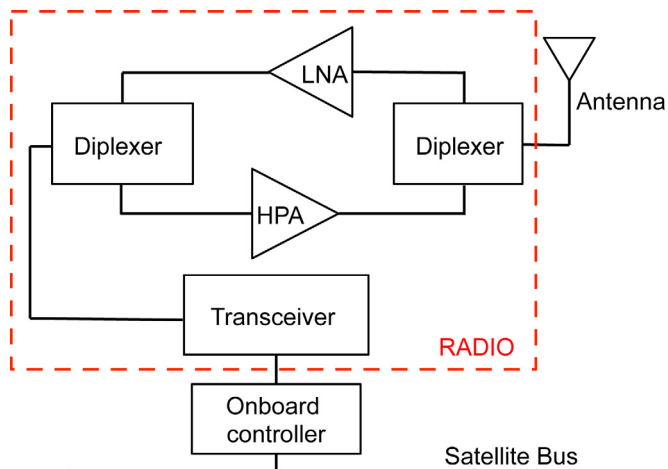
Figure 2.—A simplified block schematic of the communication subsystem.

4.3 Low Noise Amplifiers (LNA) and High Power Amplifiers (HPA)

At the operating frequencies indicated above, the noise figure of LNAs is typically on the order of 0.5 to 0.7 dB. The gain is in the range of 15 to 20 dB. The output power of HPAs typically ranges from 0.5 to 2 W, which is adequate to close the link at the above mentioned data rates.

5.0 Examples of NASA's Small Satellite Communication Technology Missions and Demonstrations

In the section below, NASA's two CubeSat Technology Demonstration missions, one Smallsat Network mission, three CubeSat flight demonstration missions and three Smallsat Technology Partnership Projects will be briefly described.

5.1 PhoneSat Missions

The first PhoneSat housed in a 1U CubeSat platform and launched into a low Earth orbit (LEO) in April 2013 was to validate the use of smartphone and other commercially available consumer-grade electronics in space (Ref. 2). Subsequently, in November 2013 and April 2014, PhoneSat 2.4 and PhoneSat 2.5 mission were launched. All of the above served as technology demonstrations and risk mitigation precursor missions to the upcoming Edison Demonstration of Smallsat Networks (EDSN) Mission, which is described below. They also provided further confidence in the PhoneSat concept and electronic components by investigating their survivability in space radiation environment.

5.2 Edison Demonstration of Smallsat Networks (EDSN) Mission

This mission will launch in early 2015, eight, 1.5U CubeSats into LEO (~500 km) (Ref. 3). These satellites based on PhoneSat architecture will have cross-link communications capability and perform a wide range of scientific research. The primary goal of the mission is to demonstrate that a swarm of nanosatellites can be configured to simultaneously gather multi-point science data and downlink the data to a ground site. The cross-link and downlink communications are at UHF and S-band frequencies, respectively.

5.3 Optical Communications and Sensor Demonstration (OCSD)

The OCSD mission will consist of two, 1.5U CubeSats in near-circular LEO with an inclination of 34° (Ref. 4). The first objective of this mission is the demonstration of a space-to-ground optical communications link at 1064 nm wavelength. The target data rate achievable with this system is on the order of 5 Mbps, which is faster by two orders of magnitude than the current capability at UHF.

The second objective is to demonstrate a small automotive anti-collision radar sensor (77 GHz) repurposed to determine the range between the two CubeSats in close proximity. Recent studies indicate that a laser rangefinder is better suited for this task since it is smaller, lighter, requires less prime power, and has multi-kilometer range. The two CubeSats equipped with this sensor will maneuver to within 200 m of each other using on-board GPS to determine their relative position and velocity. Proximity operations capability will enable multiple small spacecrafts to operate cooperatively in a science mission, approach another spacecraft for observation/servicing, or fly in-formation to form a synthetic aperture radar (SAR) for Earth surface mapping. The OCSD mission will be launched in 2015.

5.4 Integrated Solar Array and Reflectarray Antenna (ISARA) for High Bandwidth CubeSat

The ISARA mission will demonstrate a Ka-band (26 GHz) high gain (~35 dB) reflector antenna using the back of a 3U CubeSat's deployable solar array panel as a reflector (Ref. 5). The projected data rates are as high as 100 Mbps from LEO, which are several orders of magnitude higher than the data rates achievable at the UHF band. The above high-bandwidth communications demonstration will enable small satellites to perform radar/radiometry science missions that were previously only possible on large satellites. The projected launch date is late 2015.

5.5 CubeSat Proximity Operations Demonstration (CPOD)

Two 3U CubeSats will be launched in 2015/16 time frames with the objective to demonstrate (Ref. 6): (1) Ability to remain at determined points relative to each other on-orbit. This capability is essential for inspection/servicing of satellites or remote sensing of an asteroid in support of a science mission. (2) Precision circumnavigation using imaging sensor and cold gas propulsion systems. (3) A universal docking mechanism. The ability to circumnavigate and dock is essential for flying information or joining to form a large orbiting structure, such as a mirror for a telescope. During navigation, visual images of each CubeSat will be transmitted via a space-to-ground link to the control center for ensuring proper operations. In addition, GPS information will be exchanged between the two CubsSats via an inter-satellite link.

5.6 Network and Operation Demonstration Satellite (NODES)

This mission will build on the successes of the PhoneSat series of missions presented earlier (Ref. 7). In addition, it will exploit the knowledge from the experience gained in the development of hardware and software for the EDSN mission. In this mission, two 1.5U cubeSats will be launched from the International Space Station (ISS) with the objective to demonstrate software that can perform command and data handling tasks. The mission plans to showcase this capability by relaying ground commands through one CubeSat to the second CubeSat. In addition, science instruments on each CubeSat will measure the space radiation in the proximity of the ISS and relay the information to ground. The deployment is expected to take place in early 2015.

5.7 High Rate CubeSat X-band/S-band Communication System

The goal of this technology demonstration project is to develop a high data rate X-band CubeSat communication system that is compatible with NASA's Near-Earth Network. Preliminary investigations indicate that a communication system operating at a center frequency of 8.38 GHz can be built using commercially available parts (Refs. 8 and 9). The link simulations assume a transmit power of 1 W, transmit waveform to be QPSK with FEC capability, and transmit antenna gain of 0 dBi. The target data rate achievable from LEO with this system is on the order of 12.5 Mbps with a ground antenna diameter of 12 m.

5.8 Development of Novel Integrated Antennas for CubeSats

CubeSats make use of a wire or tape antenna for communications. The disadvantage of this type of antenna is that they require a deployment mechanism and are also prone to damage, which can lead to mission failure. Hence, the goal of this project is to demonstrate low-profile transparent microstrip antennas that are conformal to the surface of the solar panels of a CubeSat. Initial design studies indicated that a meshed patch antenna on a transparent quartz substrate is an excellent candidate for generating a linearly polarized (LP) antenna pattern at 2.4 GHz (Refs. 9 and 10). Extending this design to a CP version is also planned. The pioneering development of optically transparent microstrip patch antennas on flexible and on glass substrates is reported in References 11 and 12.

6.0 Example of NASA's In-Space Validation of CubeSat Based Microwave Small Instruments and Subsystems for Earth Science Measurements

6.1 The Microwave Radiometer Technology Acceleration (MiRaTA) CubeSat

This CubeSat mission will validate the following new subsystem and measurement technologies (Ref. 13): (1) Ultra compact and low-power radiometers operating at 52 to 58 GHz, 175 to 191 GHz, and 206 to 208 GHz. (2) GPS receiver and antenna array for tropospheric radio occultation sounding. (3) Radiometer calibration using concurrent GPS radio occultation measurements. The above set of demonstrations will significantly enhance the capabilities of future weather and climate sensing microwave instruments.

7.0 Summary of European Small Satellite Communication Technology Demonstrations

The CubeSat community in Europe has made tremendous strides in the development of inflatable and printed antennas, Global Navigation Satellite System (GNSS) receivers, transponders, software defined radios, and networked ground receiving stations, etc., for small satellites. References 14 and 15 are good sources of information on these developments.

8.0   Conclusion

Small Satellites such as CubeSats, NanoSats and MicroSats is an emerging disruptive technology area with a broad range/scope of applications in the RF and Communications fields. While the scope of applications is still being studied, it is clear that this technology offers tremendous benefits in many space applications. These benefits can be further enhanced through the use of 3D printing technology, which has the potential to significantly reduce the manufacturing cost, total time for the design cycle, and material waste.

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