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INVITED PAPER

Advanced Antennas for Small Satellites

This paper presents a comprehensive review of recent development in antennas for wireless systems (telemetry, tracking and control, high-speed data downlink, radars, navigation and remote sensing, intersatellite links) onboard small satellites (MiniSat, MicroSat, NanoSat, CubeSat).

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ABSTRACT | Antenna is one of the key components onboard small satellites as its design determines the performance of all the wireless systems including telemetry, tracking and control, high-speed data downlink, navigation, intersatellite communications, intrasatellite communications, wireless power transfer, radars and sensors, etc. This paper presents a review of recent development in advanced antennas for small satellites (MiniSat, MicroSat, NanoSat, CubeSat, etc.). A number of recent examples of antennas for small satellite applications are shown and discussed. A conclusion and future development in antennas for small satellites are given in the end.

KEYWORDS | Antennas; small satellites; CubeSat; MiniSat; MicroSat; NanoSat; PicoSat

I. INTRODUCTION

Small satellite is one of the fast growing sectors in space industries. Small satellites usually refer to satellites below 500 kg, including minisatellite (100–500 kg), microsatellite (10–100 kg), nanosatellite (1–10 kg), picosatellite (0.1–1 kg), and femtosatellite (<0.1 kg) [1]–[5]. Modern technology developments such as integrated circuits, miniaturization, and microelectricalmechanical systems (MEMS) have improved their capabilities, enabling satellites to become small and capable. During recent years, small satellites have become increasingly important for space industries due to the advantages of low mass, fast development, flexibility, and low cost. There are numerous research programs on small satellite research and development worldwide. For example, the National Aeronautics and Space Administration Small Spacecraft Technology Program (NASA SSTP) develops and demonstrates new capabilities employing the unique features of small satellites for science, remote sensing of Earth, exploration, and space operations [1]. The Japan Aerospace Exploration Agency (JAXA) has conducted a series of research and development programs on small low-cost satellites since the first small satellite "Micro-LabSat" was launched in 2002 [6]. Similar programs exist in the United Kingdom and Europe where the U.K. Space Agency and the European Space Agency (ESA) have many programs on small satellites and/or related technologies. One example is ESA's "Fly Your Satellite!" program which allows student teams of ESA Member States to participate in the conception, development, and integration of a small satellite project ahead of testing and, eventually, launching into orbit [7]. Recently, small satellites, in particular the CubeSat, have shown explosive growth worldwide. As of January 2016, 45 countries have launched <50-kg satellites.

Antennas are key components that enable small satellites to receive and transmit electromagnetic signals. Onboard small satellites, there are a number of antennas for different functions. Due to limited volume onboard small satellites, it is important to optimize the antenna designs, which directly

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Table 1 Key Challenges of Small Satellite Antennas Development and the Reasons

Challenges	Reasons
High reliability	Risk of mission failure
Small stowage volume, low mass, low power, efficiency and cost	Small size, low mass and low cost requirements of small satellites
Mechanically robust / rugged	Survive launch
Maintain stable electrical characteristics over a large temperature variation	Space environment: antenna gets very hot or cold depending on solar illumination
Active antennas able to survive the harsh radiation environment in space	Radiation in space environment has three sources including (1) the Van Allen radiation belts; (2) solar proton events and solar energetic particles; and (3) galactic cosmic rays. The high doses of radiation can damage electronic components
Materials selection to survive space environment	Material issues include thermal (CTE effects, low/high temperature failure of adhesives, etc.), radiation effects (charging or structural degradation of dielectrics), atomic oxygen in LEO degrades material surfaces, thermal/optical properties (i.e. absorptivity / emissivity)
Electromagnetic compatibility (EMC) and mutual coupling amongst antennas fitted in a small space	The mutual coupling amongst antennas and components onboard satellite causes the performance of antennas and electronic subsystems to deteriorate
Physical size of the satellite structure is often comparable to the wavelength of the RF signals; must analyze entire satellite structure as an integral part of the antenna design	The structures of small satellite radiate, too. The interactions between the satellite structure and the antennas need to be taken into account by including the satellite structure as a part of antenna systems
Control material outgassing (the release of a gas that was dissolved, trapped, frozen or absorbed in some materials)	Outgassing can contaminate other spacecraft subsystems, lead to structure distortion and change properties of some materials
Electrostatic charging	This can cause abnormal behavior of electronic circuits and damage dielectric materials
High power breakdown (multipaction or ionization),	High-power breakdown can damage antennas and microwave components
Passive Intermodulation (PIM)	PIM distortion degrades the quality of wireless communication systems

determine the performance of all wireless systems onboard satellites, such as telemetry, tracking, and control (TTC), high-speed data downlink, navigation, intersatellite communications, intrasatellite communications, wireless power transfer, radars and sensors, etc. Table 1 summarizes some of the key challenges of small satellite antennas development and the reasons. As shown, it is necessary to achieve miniaturization of antennas with optimum performance while the use of materials in antennas needs to take into account space environments.

This paper is organized as follows. Section I provides an introduction to small satellites and antennas. In Section II, several small satellite missions are explained. A number of recent examples of antennas for small satellite applications (MiniSat, MicroSat, NanoSat, CubeSat, etc.) are shown and discussed in Section III. A conclusion and future development in antennas for small satellites are given in Section IV.

II. SMALL SATELLITE MISSIONS

There are several small satellite missions such as the Disaster Monitoring Constellation (DMC), Small Demonstration Satellite (SDS), NovaSAR, Constellation of Small Satellites for Mediterranean basin Observation (COSMO-SkyMed), The Gravity Recovery and Interior Laboratory (GRAIL) [8], etc. Some of them are summarized below.

Disaster Monitoring Constellation (DMC) consists of a system of remote-sensing minisatellites operated for the Algerian, Turkish, Nigerian, Chinese and U.K. governments. The DMC provides emergency Earth imaging for disaster relief. It can provide large areas of imagery within a short time, due to the use of multiple small satellites in orbit ready to cross over a point of interest, and the large images produced. This delivers the responsiveness needed for emergencies and for disaster support, with images provided across the internet from the responsive satellite and a member country's ground station within one day or less after a request being made. The DMC has monitored the effects and aftermath of the Indian Ocean Tsunami (2004), Hurricane Katrina (2005), and many other floods, fires,

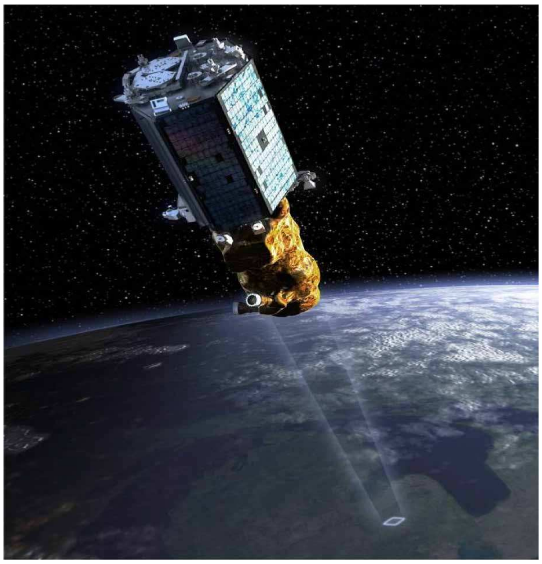


Fig. 1. ***DMC-3 satellite, courtesy of SSTL, U.K. [9].***

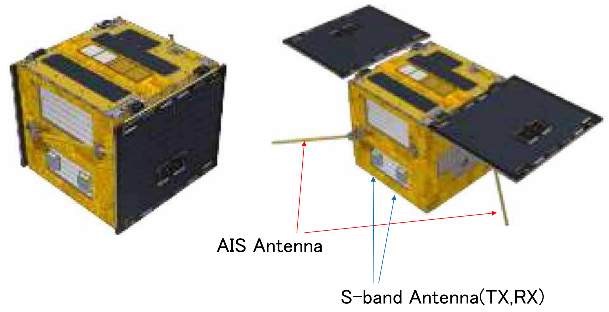
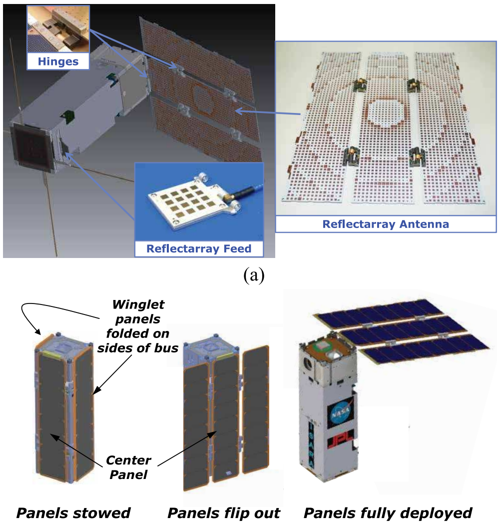


Fig. 2. ***SDS-4 microsatellite in launch configuration (left) and in deployed configuration (right) [10].***

and disasters. It has progressed into its second generation since its first DMC satellite launched in 2002. Fig. 1 shows a DMC-3 satellite launched in 2015. This satellite has a mass of 447 kg and provides 1-m high-resolution imagery with high-speed downlink (320 Mb/s) and 45° off pointing [9].

Small Demonstration Satellite (SDS): SDS-4 is a follow-on technology demonstration mission of SDS-1 heritage, based on the SDS standard bus of the Japan Aerospace Exploration Agency (JAXA). The main mission of the SDS-4 microsatellite is to demonstrate the space-based automatic identification system (AIS) experiment, quartz crystal microbalance (QCM), flat-plate heat pipe on-orbit experiment (FOX), and In-flight experiment of Space materials using THERME (IST) technologies developed by a JAXA-CNES joint research project. In addition, the SDS-4 project seeks to demonstrate the various bus components which were developed for microsatellites, such as: OBC, PCU, TRx, the small MEMS rate sensor, and the QPSK communication technology. Fig. 2 shows the SDS-4 microsatellite in deployed configuration and in launch configuration [10]. AIS antennas and S-band antennas onboard SDS-4 satellite are indicated in Fig. 2. SDS-4 is JAXA's first zero-momentum three-axis controlled 50-kg class microsatellite, launched in 2012.



(a)

(b)

Fig. 3. ***ISARA antenna: (a) key components; and (b) illustration of reflectarray panel stowage and deployment.***

Integrated Solar Array and Reflectarray Antenna (ISARA) is a mission funded by NASA SSTP with the goal of demonstrating >100-Mb/s data downlink capability on a 3U ($10 \times 10 \times 34$ cm^3) bus [11], [12]. Launched in November 2017, the key enabling technology is a folded panel reflectarray (FPR) high gain antenna that provides 33.5-dBi gain at 26 GHz [13]. As shown in Fig. 3(a), the antenna comprises three 33.9-cm × 8.26-cm reflectarray panels and a microstrip patch feed. The panels are stowed by wrapping around three sides of the CubeSat bus and deployed by means of spring loaded hinges [Fig. 3(b)]. An important advantage of the ISARA design is that the FPR panels are stowed in the empty volume that exists between the launch rails and consequently do not use any spacecraft stowed volume. In addition, an array of solar cells mounted on the opposite side of the FPR panels provides more than 20 W of prime spacecraft power. Thus, ISARA technology enables high data rate telecom and provides spacecraft power while leaving available payload volume for science instruments. The mission demonstrates this by including a secondary payload known as the CubeSat Multispectral Observation System (CUMULOS) [14], an experimental Aerospace Corporation remote sensing payload used to test the performance of passively cooled commercial sensors for weather and environmental monitoring missions.

The ISARA technology, developed by the Jet Propulsion Laboratory (JPL), will be validated during a five-month mission that uses a spacecraft and ground station network developed by The Aerospace Corporation. The mission will perform a calibrated antenna gain and radiation pattern measurement by transmitting from LEO orbit to a Ka-band ground station at JPL. It is worthwhile to note that this mission includes a number of technical advancements, including the first reflectarray antenna flown in space, first demonstration of a high gain antenna integrated with solar panels, and the first space calibrated antenna gain measurement.

Radar in a CubeSat (RainCube) is a mission funded by the NASA Science Mission Directorate's Research Opportunities in Space and Earth Science program with the goal of demonstrating Ka-band precipitation profiling radar technology on a low-cost 6U CubeSat platform [15]. There are two key elements of the technology demonstration, both developed by JPL: a new architecture for miniaturized Ka-band radar and a deployable 0.5-m Ka-band parabolic reflector antenna that stows in 1.5U. The 35.75-GHz nadir-pointing radar will measure precipitation profiles up to 18 km above Earth with a horizontal resolution <10 km and vertical resolution <250 m. Payload data and spacecraft telemetry are downloaded via ultrahigh-frequency (UHF) or S-band links. The RainCube antenna, a slightly modified version of the Ka-band antenna discussed in Section III-B, achieves 42.6-dBi gain and 52% aperture efficiency [16]. The RainCube mission, scheduled to launch after April 2018, is based on a 6U CubeSat

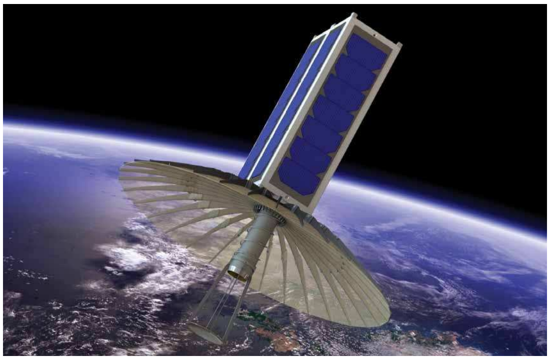
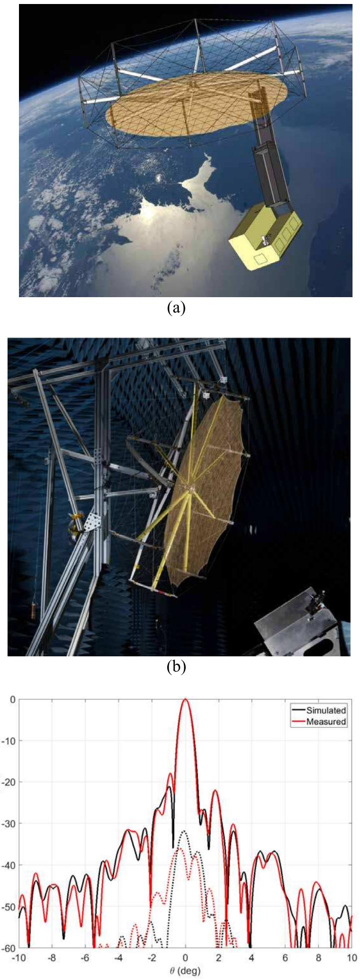


Fig. 4. ***Illustration of RainCube spacecraft with 0.5-m deployable mesh reflector antenna.***



(a)

(b)

(c)

Fig. 5. ***Illustration of 1-m offset-fed deployable mesh reflector antenna. (a) An artist on-orbit rendition [18]. (b) Prototype antenna pattern test with gravity offload fixture at JPL near-field measurement facility. (c) A representative E-plane far-field pattern comparison between the measured and simulation results at 35.75 GHz.***

bus developed by Tyvak Nanosatellite Systems, who is also responsible for mission operations. RainCube is expected to be the first space flight demonstration of a CubeSat radar and will succeed in raising the technology readiness level (TRL) from the current 4–5 to 7. Fig. 4 illustrates an artist concept of the RainCube spacecraft and the antenna.

Following the successful demonstration by JPL [17] of the 0.5-m RainCube reflector concept, it has been planned to evolve the design for the next generation of CubeSats. Challenging Ka-band remote sensing applications require an antenna aperture of at least 1 m, spurring on a collaborative effort between NASA, JPL, and the University of California at Los Angeles (UCLA) in targeting a next generation of large aperture high-gain CubeSat mesh reflector antennas. Mechanical constraints coupled with millimeter-wave (mm-wave) frequency sensitivities prohibited scaling of the 0.5-m umbrella reflector designs, mainly because an efficient 1-m reflector design requires more than 30 ribs, which greatly increases the risk of rib jamming during deployment. Attempts were subsequently made to develop a completely new 1.0-m reflector design that stows in roughly a 3U ($10 \times 10 \times 34$ cm^3) CubeSat volume.

Though a symmetric reflector configuration has its advantages, the feed deployment mechanism also becomes complex since the feed has to deploy and face either the reflector or the subreflector. To balance these tradeoffs, a single offset-fed reflector configuration was chosen. The offset configuration alleviates some of the difficulties encountered during the deployment of symmetric reflectors. Fig. 5(a) shows an illustration of the offset deployable mesh reflector concept developed by Tendeg [18].

A challenge for the CubeSat system is designing a feed that optimally illuminates the reflector while satisfying the mechanical constraints imposed by the CubeSat standard at a reasonable cost. In order to ensure minimum spillover, the sidelobes and backlobes of the horn must be minimized. Further, the S_{11} must be as low as possible. A novel spline-profiled smooth walled horn design (developed at UCLA) was employed to strike a balance between ease of fabrication, cost, desired radiation characteristics, and overall volume [19]. Particle swarm optimization (PSO) [20]–[21] was used to obtain the optimal design for the horn.

The goal has been to package the entire antenna system into a roughly 3U volume for a 12U CubeSat, as illustrated by the artist's rendition in Fig. 5(a). The offset reflector geometry uses an F/D of 0.75 with a clearance height of 0.13 m. These design values are a nice compromise between mechanical complexity, RF performance, and feed design simplicity. A photo of the first prototype reflector mounted in the JPL antenna range is shown in Fig. 5(b). This antenna achieved a measured gain of 49.2 dB at 35.75 GHz, corresponding to a 59% aperture efficiency. The antenna has nearly equal E-plane and H-plane half-power beamwidths (HPBWs) of 0.57° and 0.53°, respectively. A representative E-plane far-field pattern comparison between the measurement and simulation is shown in Fig. 5(c). Excellent agreement is observed.

III. ANTENNAS FOR SMALL SATELLITES

A. Antennas for Small Satellite TTC Subsystems

Small satellite TTC subsystems require antennas to receive the uplink signals for telecommand purposes and transmit downlink telemetry signals. TTC antennas should achieve their performance whatever the attitude of the small satellite, thus the antennas need to have compact size, full spherical coverage, low loss, and high reliability. The full spherical coverage is often achieved by combining the radiation patterns of several antennas located at different areas of small satellites, as one single antenna is unable to provide the full spherical coverage. The frequency bands include very high frequency (VHF), UHF, S, X, Ku, and Ka bands. Since TTC data rates are generally low, narrow bandwidth antennas are acceptable. Typical antennas include monopoles, microstrip patches, helices, and turnstile antennas. For TTC of microsatellites and minisatellites, microstrip patch antennas are often employed and Fig. 6 shows an S-band patch antenna [22]. The antenna is robust and can be easily integrated with satellite body. For TTC of CubeSats and NanoSats, monopoles are often employed, and one example is the deployable antenna systems from Innovative Solutions in Space (ISIS) which contain up to four tape spring antennas of up to 55-cm length [23]. The deployment system relies on a thermal knife composed of one wire and two redundant heating elements per tape. Radio-frequency (RF) phasing and balun circuitries tie the antennas together in a monopole and dipole configuration. The antenna is useful for CubeSat TTC at UHF and/or VHF bands.

B. Antennas for Small Satellite High-Speed Data Downlink

After the satellite achieves stabilization, it will need the high-speed data downlink subsystem to download a large amount of data to the ground station. Compact-size high-gain antennas are usually required to achieve high-speed data transmission.

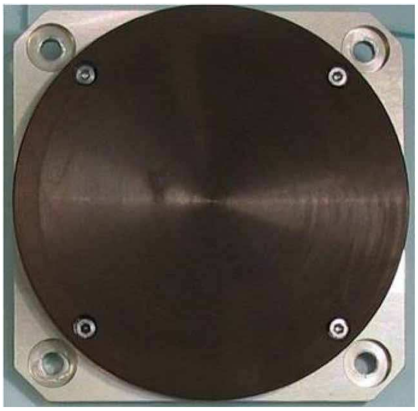


Fig. 6. ***S*-band patch antennas, courtesy of SSTL.**

Fig. 7. ***Antenna pointing mechanism with horn antenna, courtesy of SSTL.***

High-gain antennas requires accurate pointing of their beams. Thus, for small satellites without high-precision attitude determination and control system (ADCS), a medium gain (up to ~12 dBi) is often used. With the recent advances of ADCS for small satellites, antennas with much higher gain are expected to play roles in data downlink. To compensate for the differences in free-space propagation losses caused by the curvature of Earth's surface, the ideal radiation pattern is an isoflux coverage. The frequency bands typically use S-band and X-band. Recent trends are to employ Ka-band and higher frequencies, due to the need for wider bandwidth for downloading more data at higher speed.

Figs. 7–9 show some antennas for microsatellites and minisatellites, while Figs. 10–13 show some antennas for CubeSats and NanoSats.

Fig. 7 shows the X-band high-gain horn antenna from SSTL [24]. The antenna can be mechanically steered toward the ground station while satellite is moving. This antenna can radiate either right- or left-hand circularly polarized signals by altering the position of the feed. It operates at X-band, providing a gain of 15 dBi at boresight and 3-dB beamwidth of 25°. The antenna can achieve a wide scanning range, is robust, and has low cost.

Planar antennas are attractive for small satellites as they can be easily integrated with the satellite body. Fabry–Perot cavity can be employed to improve the gain of planar antennas, and one example of wideband circularly polarized planar antenna using Fabry–Perot cavity is shown in Fig. 8 [25]. It has a two-layer partially reflective surface with positive reflective phase gradient which improves the gain bandwidth of the antenna. The X-band prototype demonstrates a 3-dB gain bandwidth of 28.3% from 8.8 to 11.7 GHz with a peak gain of 14.7 dBi. The antenna has a low profile, a simple feed network, and low cost.

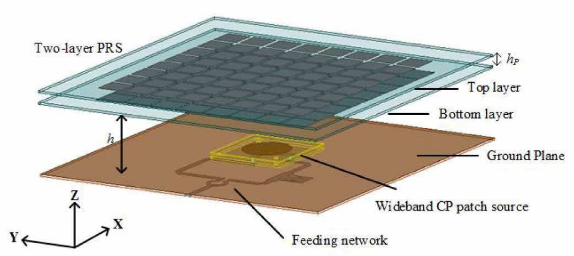
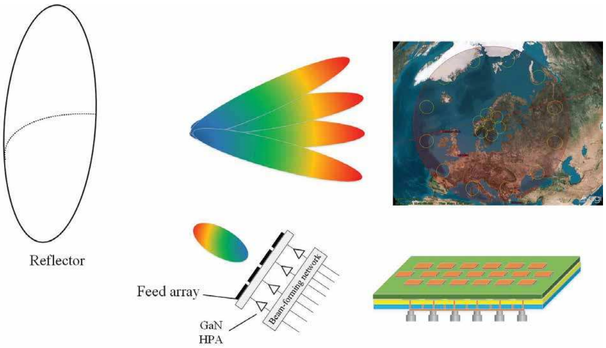


Fig. 8. ***Fabry–Perot cavity antenna for small satellites.***

Fig. 9 shows the antenna developed within the European project GaNSat funded by the European Commission [26], [27]. A parabolic reflector is fed by a planar active phased array integrated with high power amplifiers (HPAs) and low-noise amplifiers (LNAs) in GaN. Due to the advantage of high power density of GaN technology, the HPA module is significantly reduced in size and mass. The single GaN HPA chip obtains an output power of 10 W and a gain of 16 dB from 18 to 20 GHz. The radiating element of the phased-array feed is wideband dual-CP stacked patches with multilayer configuration. The patch is fed by two microstrip lines which are connected to the outputs of the branch line couplers printed in different PCB layers.

Limited space available onboard small satellites is a key problem for high-speed data downlink and radar payloads. Recently, a variety of deployable antenna technologies have been developed to address this need. Deployable reflectors enable an antenna to be compact in stowed configuration and become fully deployed in orbit. Fig. 10 shows a 0.5-m mesh deployable parabolic reflector designed to fit in a 1.5U (10 × 10 × 15 cm^3) CubeSat stowage volume [28]. The reflector surface consists of a knitted gold-plated tungsten wire mesh with a surface density of 40 openings-per-inch (OPI) that is supported by 30 hinged ribs. Deployment is driven by a motorized planetary gear system along with a spring loaded “pop out” feed and subreflector assembly. This antenna has been adapted for both CubeSat telecom and radar applications. The telecom version is compatible with NASA’s deep-space network (DSN) at the Ka-band downlink (31.8–32.3 GHz) and uplink (34.2–34.7 GHz) frequency bands. It achieves 42.0-dBi gain and 57% aperture efficiency at 32 GHz. The radar antenna design has been fully flight qualified (i.e., thermal and vibration testing) and is planned to fly on the RainCube radar in mid-2018.



(a)

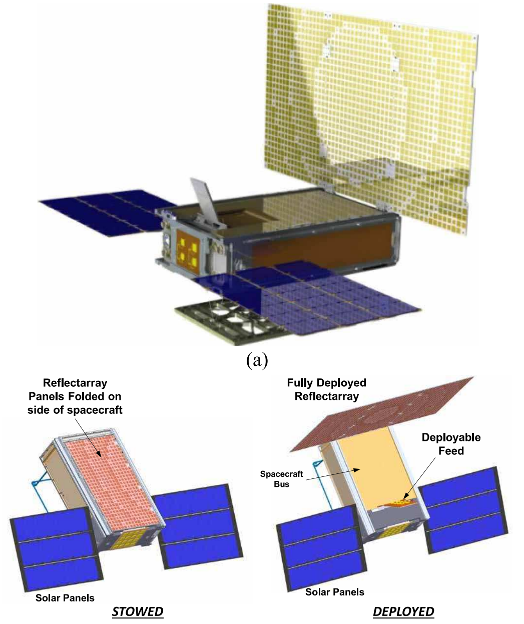
(b)

Fig. 9. ***Antenna in GaNSat. (a) Antenna configuration. (b) Feed structure and beam coverage on Earth.***

Fig. 10. ***Deployable reflectors for CubeSats.***

Folded panel reflectarray (FPR) technology provides another way to realize a deployable high gain antenna [29]. A reflectarray antenna consists of a special reflecting surface along with an illuminating feed [30]. The reflecting surface comprises an array of phase control elements, such as microstrip patches, printed on a circuit board using standard photo etching processes. The phase control elements are adjusted to collimate the reflected feed illumination, much as a parabolic reflector would. However, unlike a parabolic reflector, the reflectarray panels are flat, which permits them to be folded and stacked for compact stowage. FPR antennas offer several notable advantages compared to deployable parabolic reflectors, including stowage efficiency, beam pointing and beam shaping flexibility, rapid development, and lower cost. Further, the printed circuit board construction readily accommodates solar cells, enabling integration of the antenna with solar array panels, either on the back side as done for ISARA [13] or on the reflectarray side by using optically transparent reflectarray elements [31]–[35]. However, FPR antennas are narrow band devices (typically a few percent bandwidth) and the aperture size is limited by the practical number of folds.

As an example, Fig. 11(a) shows the reflectarray antenna designed for the NASA Mars Cube One (MarCO) mission [36]. The MarCO CubeSat is planned to fly to Mars and provide a real-time bent-pipe telecom link during the InSight mission’s entry, descent, and landing (EDL) phase. Scheduled to launch in 2018, MarCO will likely be the first interplanetary CubeSat mission. The antenna design challenge was to develop a flight-qualified 28-dBi gain X-band antenna that used a small fraction of the 6U (10 × 20 × 34 cm^3) CubeSat bus volume with less than 2-kg mass at low cost



(a)

(b)

Fig. 11. ***MarCO antenna. (a) Spacecraft assembly illustrating deployed reflector antenna. (b) Illustration of reflectarray panel stowage.***

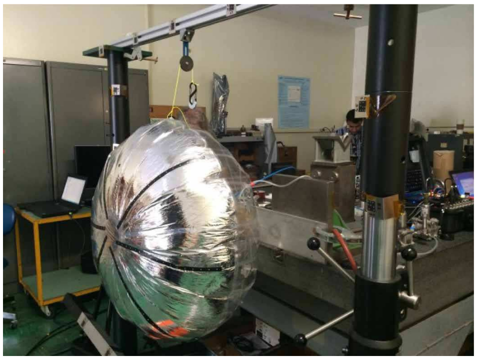


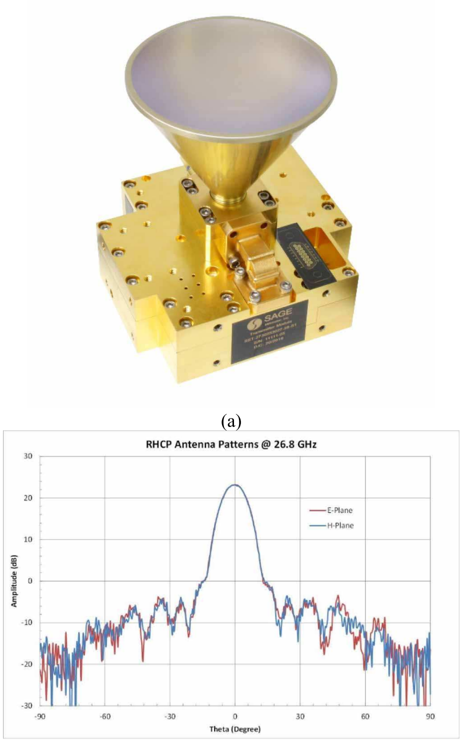
Fig. 12. ***Inflatable antenna for CubeSats: Development of the X-band prototype [38], courtesy of JPL.***

in one year. To do this, a three-panel FPR was designed to fold onto the side of the 6U bus and fit between the bus and the launch canister [Fig. 11(b)]. A microstrip patch feed fits below the FPR and pops out during panel deployment. Compact spring-loaded hinges enable the unit to fold into a 1.25-cm-thick package which only consumes ~4% of the usable spacecraft payload volume with a mass of <1 kg. The antenna provides a gain of 29.2 dBic (an efficiency of ~42%) with right-hand circular polarization (RHCP).

There are several other notable methods to stow a high gain antenna. Inflatable antennas were the subject of research for many years as a way to create large (>5-m diameter) reflectors with very high stowage efficiency. However, only the 1996 Inflatable Antenna Experiment, a 14-m diameter parabolic reflector, has flown in space [37]. The key challenges with inflatable antenna technology are surface accuracy and the method used to rigidize after inflation so that gas leakage does not pose reliability problems. Although these problems were not adequately addressed for large reflectors, there is renewed interest in inflatables for small satellites resulting from their shorter mission lifetime, risk tolerance, and smaller apertures. Fig. 12 illustrates a recent example of a 1-m inflatable antenna for X-band [38]. Realizing the parabolic surface shape proved to be challenging, but a spherical reflector has shown promise [39].

A tensioned membrane inflatable reflectarray offers an alternative antenna architecture that permits the use of a flat, instead of a curved, antenna surface [40]–[42]. This antenna concept uses two thin Kapton membranes which are pulled flat by a perimeter truss structure, similar to a drum head [43]. The two surfaces are metallized to create a reflectarray. A flat surface is comparatively easier to fabricate, package, and maintain than a curved surface. The antenna can employ inflatable/self-rigidizable technology in its primary structural members, thus allowing the reflectarray antenna to be collapsed and packaged into a small launch volume. This concept has received interest as a potential high gain antenna for small satellites and was also used to successfully demonstrate an S-band microstrip patch array [44].

Fig. 13(a) shows a Ka-band lens antenna for CubeSats and nanosatellites [45]. A waveguide E-plane bend is used to couple the transmitting signal into a circular polarizer



(a)

(b)

Fig. 13. ***Ka-band lens antenna, courtesy of SAGE Millimeter, Inc.***

and lens antenna for efficient power radiation. The antenna assembly has 23-dBi gain, which allows the transmitter module to deliver over +50-dBm EIRP for the final transmitted signal. Fig. 13(b) shows the radiation pattern of the antenna. It demonstrates symmetric patterns in both E- and H-planes.

Other examples include the printed monofilar square spiral antenna [46], reconfigurable/deployable helix [47], polarization-reconfigurable cavity-backed slot antenna for CubeSat [48], shorted annular patches [49], etc.

C. Antennas for Synthetic Aperture Radars (SARs) Onboard Small Satellites

SAR has become increasingly important for small satellites due to strong needs of Earth observation during all days and nights and under all weather conditions. Small satellite SAR usually requires antennas to have multiple frequency bands, dual polarizations, electronic beam steering in both planes, high efficiency, beam-shaping capability, compact size, low mass, and low power. SAR antennas are typically quite large and require narrow azimuth and wide elevation beamwidths.

NovaSAR-S is a SAR mission operating at S-band and designed for low-cost programs [50]. It is a joint technology demonstration initiative of SSTL, U.K., and Airbus, U.K. Fig. 14 shows the antenna in Nova-SAR [51]–[52]. The antenna array in the NovaSAR-S system is a microstrip patch active phased array consisting of 18 subarrays. The total size of the antenna array is 3 m× 1 m. Multiple polarizations, including VV, HH, VH, and HV, can be achieved using this antenna system. To obtain electronic beam steering, the antenna is integrated with microwave phase shifters which are controlled by direct current (dc) voltages. GaN technology is employed in NovaSAR-S to reduce the size, mass, and cost of the SAR antenna system due to the high power density capability of GaN devices in comparison to conventional GaAs technologies.

Fig. 15 shows the 100-kg class SAR satellite from JAXA [53]. Fig. 15(a) shows both the stowed and the deployed configurations of satellites with the SAR antenna. The SAR system requires an antenna of several meters in orbit while the stowed size of the satellite should be $< 0.7 \times 0.7 \times 0.7\ \text{m}^3$ for piggyback launch. The antenna employed is a deployable planar antenna using seven sections of single-layer slotted waveguides. Fig. 15(b) shows one section of the antenna structure. The slot array antenna consists of dielectric honeycomb core plate and metal skins, which work as a dual-plate guide for RF. Its size is about 70 cm ×70 cm ×0.6 cm. The front surface with a slot array works as an antenna radiator. Waveguides are installed at two sides of the rear surface in order to feed positive-direction and negative-direction traveling wave into the dual-plate through slots at the waveguide wall. Right-hand and left-hand circular polarizations are radiated through the slots at the skin. Thus, one aperture surface can work as a dual-polarization antenna. The antenna operates at 9.65 GHz with a bandwidth of 130 MHz. An aperture efficiency of 55% is achieved.

Fig. 16 shows the antenna developed in the European project DIFFERENT funded by the European Commission [54].

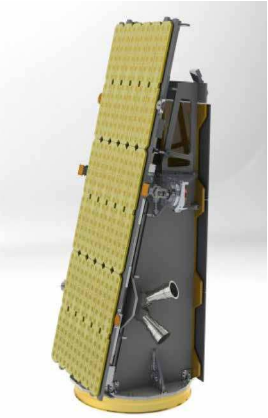
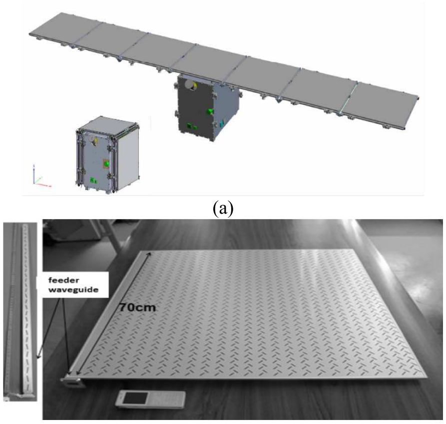


Fig. 14. ***Antenna in NovaSAR-S.***



(a)

(b)

Fig. 15. ***Deployable waveguide slot antenna.***

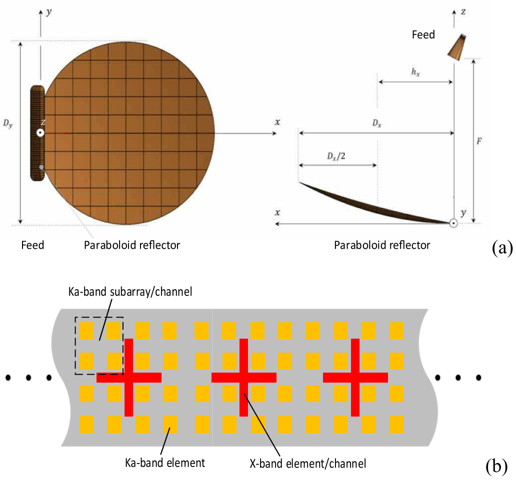


Fig. 16. ***Antenna of DBF-SAR in the DIFFERENT project. (a) Configuration of antenna system. (b) DBF feed.***

The antenna system is a deployable reflector fed by a highly integrated dual-band (Ka/X) digital beam forming (DBF) planar feed array. The parabolic reflector is defined in a Cartesian coordinate system where x-axis coincides with an along-track (azimuth) and y-axis with a cross-track (elevation) direction of the imaging platform, as shown in Fig. 16(a). To facilitate the DBF-SAR system, the X- and Ka-band radiation elements onboard are divided into separated channels, as shown in Fig. 16(b). As can be seen, the X-band and Ka-band radiation elements are interlaced with each other, sharing the same aperture. Each X-band element is connected to one channel whereas 2 × 2 Ka-band elements are combined as a subarray and connected to one channel. Both X- and Ka-band antennas operate at two orthogonal polarizations. The antennas employ crossed dipoles for X-band and dual-fed slot-coupled patches for Ka-band. The active circuits are fabricated in SiGe technology, leading to low cost.

Recently, there have also been some developments of circularly polarized SAR for microsatellites (and unmanned aerial vehicles) [55]–[56]. In [50], a deployable mesh reflector at L-band is developed for SAR onboard a microsatellite for Earth observation.

D. Antennas for Intersatellite Links

Intersatellite links are very important for small satellites. Swarms of many small satellites with intersatellite links can enable small satellite systems to achieve the functions and capabilities far beyond that of one single small satellite. Antennas for intersatellite links usually need to have high gain, for overcoming the high loss due to radio propagation over a large distance between small satellites. Also, the antennas need to have compact size and beam steering capability.

Researchers at the University of Hawaii (UH) recently developed a retrodirective array (RDA) based on a null-scanning approach with several hardware and software optimizations motivated by size, weight, and power constraints [57]. The four-element, 1-D RDA was designed to fit within a 1.5U CubeSat structure, which measures 10 cm × 10 cm × 15 cm, with a mass of no more than 1.5 kg. The design consisted of two four-layer printed circuit boards: one dedicated to full-duplex communication, the other for power detection. The two boards were interfaced by the UH CubeSat Stackable Interface for digital and power signals, and Tensolite cables for RF signals. Full-duplex retrodirectivity was reported at 9.59 and 9.67 GHz for transmit and receive, respectively. Fig. 17 shows the assembled CubeSat prototype with dimensions of 4 cm × 10 cm × 14 cm. The RDA hardware has a mass of 186 g. The dc power consumption of the various components of the CubeSat RDA prototype is 1 W, which is well within the power-generation capabilities of CubeSats equipped with either body-mounted or deployable solar panels, together with batteries for operation in eclipse.

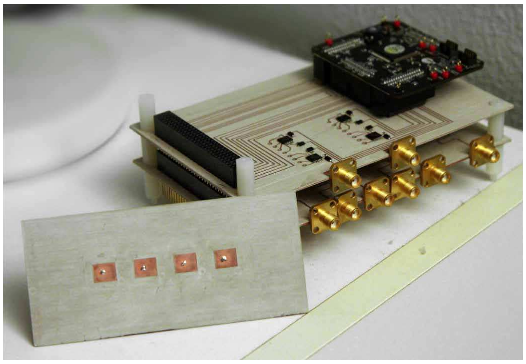


Fig. 17. ***Null-scanning retro-directive array antenna for CubeSat [52].***

Fig. 18 shows the "Bull's Eye" antenna for CubeSat applications [58]. The antenna consists of a number of annular ring slots, and is fed by a subwavelength aperture in the center which is coupled to a WR-15 rectangular waveguide on the backside. It has a maximum side length of 100 mm and a thickness of 3.2 mm, thus suitable for integration with a 1U CubeSat. The antenna achieves 19.1-dBi gain at 60 GHz and > 16.7 dBi over the 5.06-GHz bandwidth. The antenna has low cost and can be easily manufactured by milling machines.

Other antennas for CubeSat intersatellite links are also reported. In [59], a low-profile multibeam "Bull's Eye" antenna is reported. Pinho *et al.* [60] present an antenna system for intersatellite links in the GAMANET project, which aims to create a large *ad hoc* network in space using ground stations and satellites as nodes with intersatellite links at S-band. In order to achieve complete coverage for intersatellite communications, the antenna system consists of multiple microstrip patch antennas with one patch per face of the CubeSat [60].

E. Antennas for Navigation and Remote Sensing Applications

Antennas are also required for other applications such as navigation, remote sensing, AIS, intrasatellite links, wireless power transfer, and various science missions.

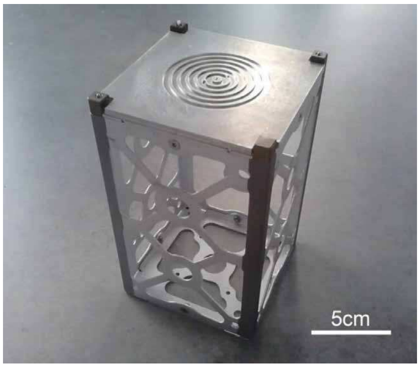


Fig. 18. ***V-band "Bull's Eye" antenna for CubeSat applications.***

One example of antennas for navigation applications is the patch-excited-cup (PEC) antenna consisting of two metallic patches placed in a circular cup [61]. To achieve stable RF performance over the GNSS frequency bands, it uses a four-point feed with capacitive coupling of the bottom patch and an isolated feed network. The antenna is suited for precise orbit determination applications, in which the stability of antenna phase center is critical. The antenna covers both L1 and L2 bands of GNSS frequencies. It has a wide coverage. The antenna has a mass of 345 g and a diameter of 160 mm. For navigation application, it is important to achieve low backward radiation for multipath mitigation. A compact multipath-mitigation ground plane for multiband GNSS antenna is reported in [62].

For GNSS reflectometry and remote sensing applications, a multiband antenna with high gain and wide beam coverage is required. Maqsood *et al.* [63] report a dual-band beam-switching planar antenna which integrates a low cost, broadband, and low-loss beam switching feed network with a dual-band antenna array to achieve antenna gain >10 dBi and continuous beam coverage of ±25° around the boresight at both L1 and L2 bands. Other antennas for GNSS reflectometry are reported in [3].

Some interesting antennas for CubeSat are summarized in [64]. The Special Issue on “Antenna Innovations for CubeSats and SmallSats,” published in the IEEE Antennas and Propagation Magazine in April 2017, contains some recent examples of antennas.

IV. CONCLUSION AND FUTURE WORK

This paper presents an overview of recent developments of antennas for small satellite applications. Many examples of antennas for various applications (TTC, high-speed data download, SAR, navigation, remote sensing) are discussed.

Looking into the future, the trends are to make antennas “smaller, smarter, cheaper, and faster.” To make the antennas smaller, one possibility is to move into higher frequencies such as Ka- and V-bands and THz. To enable a single-antenna aperture to operate over an ultrawide-frequency range, one promising technique is to employ “tightly coupled array” into reflectarray [65]. An alternative technique is to develop a shared-aperture multiband array antenna. One shared-aperture triband array antenna using Fabry–Perot cavity is reported in [66]. Another technique is to develop reconfigurable antennas with multiple functions integrated. One example is the multifunctional miniaturized slot antenna system developed at EPFL [67]. The antenna makes use of the satellite structure allowing a high integration level within the satellite body. It can be reconfigured to operate in three different modes for different functions. Another example is to integrate some circuitry functions (e.g., filtering, duplexing, and impedance matching) with the antennas [68]–[69]. Active antennas which integrate antennas with active circuits (amplifiers, mixers) can further reduce the size, power consumption, and cost of RF front ends [70]. It will also be useful to consider the integration of antenna with other components such as solar sail, solar panels, or thermal radiators. To make the antennas smarter, the antenna needs to be electronically reconfigurable in radiation patterns, polarization, and frequency bands of operation. Traditional phased arrays are too expensive and power hungry for small satellite applications, thus low-cost small smart antennas are needed [71]. A low-cost beam-steerable reflectarray using 1-b phase shifters is reported in [72]. A dual-band electronically beam-scanning antenna using slot active frequency selective surfaces is reported in [73]. It is also necessary to investigate low-loss tunable materials (ferroelectric thin films, piezoelectric materials, liquid crystals, MEMS, etc.) and their integration with antennas for forming low-cost beam-steerable antennas. To make the antennas cheaper and faster, it is important to simplify the antenna structure and consider manufacturing technologies such as 3-D printing, which has the advantages of rapid prototyping at low cost [74]. In order to achieve the optimum performance with minimum size and cost, future antenna engineers will need to have a clear understanding of both the RF system and the whole satellite system. To achieve this, efficient multiphysics/multiscale modeling and optimization of antennas with the satellite system (EM, thermal, mechanical, etc.) will be needed [75], [21]. ■

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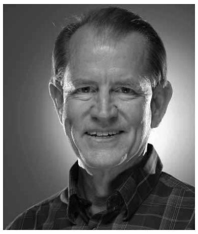

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