

Design and Review of Antennas for Picosatellite

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Abstract:

Cube satellite (CubeSat) technology is a promising new alternative to traditional satellites in radio astronomy, earth observation, weather forecasting, space research, and communications. Its size, on the other hand, imposes more stringent constraints on the circuitry and components, which must be closely placed and extremely power efficient. CubeSat antennas are one of the most important components that will require careful design because they must be lightweight, tiny in size, and compact or deployable for bigger antennas. This study provides an overview of antennas appropriate for picosatellite applications. Before delving into the antenna requirements, a summary of picosatellites' applications will be provided. The materials and antenna topologies used will be studied further before presenting numerous deployable versions. Finally, a perspective and future research on CubeSat antennas will be covered in the final section.

Key words : Cube Satellite, antennas, picosatellite, topologies.

1. INTRODUCTION

In general, satellites are structures that are capable of transmitting and receiving or relaying signals from space. Due to their location, they are able to provide a wide coverage area with long communication range. The development of the conventional satellites incurs significant amount of financial, time, and resources costs. However, a viable alternative to this is the deployment of picosatellites such as CubeSats. They cost less, consume less power, and allow fast development time but, at the same time, are feasible and robust, similar to conventional satellites.

CubeSats are satellite structures with a volume of 10 cm³ and a mass of less than 1 kg, typically made of lightweight commercial-off-the-shelf components [1]. Due to their size and weight, CubeSats are known to be part of the picosatellite family. One of the first CubeSats was developed by the California Polytechnic State University (Cal Poly) in collaboration with Stanford University starting 1999 [1] and was launched in 2002 [2]. The Cal Poly's mission was aimed at using Stanford University's spacecraft named OPAL as the proposed CubeSat launcher [1]. This project began with the development of the standard launcher known as the Poly Picosatellite Orbital Deployer (P-POD). Besides the CubeSat structure, its theoretical criteria such as the weight and the size of CubeSat must comply with the launcher's specifications to ensure a successful deployment into space [1]. Several requirements for the P-POD deployer include aspects such as a space between CubeSat edges from the rail to avoid friction and ensure smooth deployment. Besides that, extended spaces need to be available for solar panels, antennas, or other components with possible extension of more than 10 cm.

Since then, several types of CubeSats were developed with several sizes such as the 1 U standard CubeSat with a unit of cube (10 ×

10 × 10 cm³), 3 U, 6 U, and 12 U consisting of three, six, and twelve cube units. The choice of size is dependent on the installed components

and launcher's specification. They are typically placed into the low earth orbit (LEO) ranging from 160 km to 2000 km in altitude [3], with a typical lifetime of several years working in space [4]. This paper provides a comprehensive review of the applications of picosatellites and the types of antennas available in literature. Most importantly, the challenges involved in their development and the innovative methods applied to these antennas in solving the space and power limitations in such compact satellites are also discussed. The existing works on picosatellite antennas are reviewed and summarized in a systematic way, with emphasis on their important deployable parameters such as stowage location, stowed size, and stow-to-deployment ratio besides conventional antenna parameters

1.1. Applications of Picosatellites:

Satellite technology is widely used in many aspects of today's life such as television broadcasting, mobile satellite, radar and imaging applications, and weather forecasting [5]. However, the recent introduction of picosatellites has enabled their application in a small segment of the field which has been conventionally supported by larger satellites for earth observation and space weather forecasting. Due to their size and development time, costs are significantly reduced compared to conventional satellites. The applications for CubeSats have been reviewed in several previous publications [4, 6, 7]. A general CubeSat overview and its capability have been described in [6]. Meanwhile, a

general survey on the communication system of the CubeSat applications over the past several years have been discussed in [4, 7]. Besides the current applications explained in the

following sections, CubeSats are currently still being improved and adapted for use in other more specific and advanced applications. *i) Earth and Climate Observation.* Earth observation has been performed since 1960 by the United States (US) meteorological satellite [8]. A review of the requirements and capabilities of CubeSats for the earth science and observation has been performed in [8]. The purpose of earth observation is to measure earth characteristics to better understand the weather, natural disasters, pollutions, and water [9]. A satellite placed in the orbit will scan the image of the earth surface and map the focused area based on the radar concept [10]. It is also possible to measure the characteristics of soil using this technique [10] using a high gain antenna and radar. Meanwhile, the European Space Agency (ESA) and the National Aeronautic and Space Administration (NASA) have both produced their first observing satellite in 1990 and 2000 [9]. A larger satellite for this application, ENVISAT, was built by ESA [9]. It is capable of fast and efficient observation [9]. The need for picosatellites such as CubeSats was quickly realized due to the need of mass-release payloads to ensure mass efficiency using a single launch [9]. Other researches involving nano- and picosatellites have been implemented and summarized in [11, 12]. The best CubeSat researches so far include carbon dioxide measurements and GNSS radio occultation [13], a research on hyperspectral microwave atmospheric sounding by MIT's MICROMAS CubeSat [14], and gathering results of particle involving clouds and aerosol by NASA's Cloud CubeSat [15]. Besides that, CubeSats have also shown potential for education purposes. For instance, detailed earth observations have been performed using a CubeSat in [12].

For climate observation, satellite performance is crucial to ensure complete and accurate measurement results. For instance, one of the main limitations of the Tropical Rainfall Measurement Mission (TRMM) is the deployment of a number of instruments in LEO which were unable to provide complete measurement results by short-term climate observation [16–19]. However, this can be reduced by implementing the constellation of precipitation profiling instruments in LEO, at the cost of production timeline and resources [20]. Thus, CubeSat was chosen as an alternative structure for this application by optimizing its existing characteristics for a radar satellite [20].

ii) Space Weather Forecasting. Another interesting application for CubeSats is known as space weather forecasting. Its purpose is to provide an initial warning of storms in the solar system by using several CubeSats in a cluster. The concept is to forecast the weather of the solar system by establishing a CubeSat with a specific payload and high antenna performance to transmit the data with a high rate to the earth. The rest of the CubeSats will use low performance antennas for communication between each satellite within the earth's orbit [21]. In such situations, the communication links between CubeSats are crucial as they are deployed with unspecific distances from the target orbit. Besides that, CubeSats have also been used for defence forces such as the Air Force for space monitoring.

The interconnection of several CubeSats placed in LEO was able to optimize resources in such monitoring [22].

Space Research. CubeSats have also been utilized in a nanosatellite program known as the Nanosatellite Tracking of Ships *iii)* (NTS) [23]. This trial program is intended to test the satellite in a real space environment to ensure communication between the receiving part of the Automatic Identification System (AIS) receiver radio and AIS transmitter in LEO within a range of 100 km [23]. This system is capable of collecting the message from space to provide the awareness of global marine traffic and for other common applications [23]. The NTS mission is to collect the AIS signal in the LEO range, to measure the surrounding radio frequency from 160 MHz to 162 MHz with noise level identification, and to provide a platform for future mission qualification [23].

TABLE 1: Summary of the operating frequencies, data rate, and antenna gains for picosatellite applications.

Types of application	Operating frequency band		Communication performances	
	Application-specific frequency (range)	Communication with ground station (range)	Required transmitting gain	Required data rate
Earth and climate observation [9]	L-band (1-2 GHz), Millimeter wave	VHF band (130-170 MHz), UHF band (400-450 MHz), S-band (2-4 GHz)	Minimum 17 dB	More than 9600 bps
Space weather forecasting [21]	X-band (8-12 GHz)	S-band (2-4 GHz)	26 dB & 37 dB	Up to 400 kbps
Space research [24]	X-band (8-12 GHz)	VHF band (130-170 MHz), UHF band (400-450 MHz)	17 dB & 37 dB	More than 32 kbps
Communications [25]	K-band (18-27 GHz)	K-band (18-27 GHz)	45 dB	More than 6 Mbps
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The structure of NTS is only 20 cm along with two strings for solar cells, which serve as the source power of the spacecraft attitude [23].

In space research study, CubeSat can also be utilized for asteroid exploration. The significant budget for such exploration can be reduced by utilizing CubeSats [24]. Such missions can be implemented using two methods: (1) using a single CubeSat as the explorer or (2) using a conventional satellite as a carrier of the CubeSat. For such applications, the operation in X-band is preferred for deep space exploration compared to the Very High Frequency (VHF)/Ultrahigh Frequency (UHF) band and the S-band [24].

iv) Communications. Arguably the most important application of picosatellites is in the communication aspect. Identifying its requirements starts with estimating a good

link budget to ensure efficient communication between the space- to-earth or space-to-space communication links [25]. For communications between CubeSats, a higher operating frequency is preferred in the S-band, or specifically at 2.45 GHz. This is to enable signal reception by small antenna receivers using this band via the use of smaller antennas compliant to the CubeSat structure [25].

More recently, researchers have been exploring the possibility of optical communication systems in space between satellite and earth station known as quantum communications [26]. The satellite communicates by transmitting a laser in the optical field frequency range to a base station on earth with a line of sight (LOS) enabling the link establishment [26]. This concept of bidirectional communication is, however, susceptible to changes to the CubeSat position in orbit. Therefore, an additional payload with a tracking and acquisition system must be installed for CubeSat position detection. Several specifications have been proposed, including an uplink optical laser specified at 980 nm, while its downlink was specified by 1550 nm [26].

In contrast with other applications, intersatellite communication is a process of cooperation between each of the CubeSats aimed at gathering and distributing specified data to one another before data transmission to earth [25]. Multiple CubeSats mainly collaborate for deep space research and space weather forecasting. A group of CubeSats in distributed locations will individually gather required data, similar to the Orbiting Low Frequency Antennas for Radio Astronomy (OLFAR) project, the QB50 project, and applications described in the previous sections [21, 27, 28]. Such systems work like a wireless sensor network (WSN) with multiple nodes spread in space [25]. Based on projects mentioned in [28, 29], each of the satellites will connect to each other and share all information such as timing, positioning, and other related information, including the observation data. Another example of such communication system is the IRIDIUM satellite constellation, which uses frequencies ranging from 22.55 GHz to 23.55 GHz to enable stable route traffic via intraplane and interplane neighboring satellites [30–32].

II. REQUIREMENTS FOR PICOSATELLITE ANTENNAS

The effectiveness of the CubeSat communication system is determined by the link budget estimates, and one of the important components determining this is the performance of the antenna. The size of the antenna on the CubeSat structure is dependent on the required gain and operating frequency. Due to the need for multielement antenna arrays to boost gain, the use of miniaturization techniques is crucial in ensuring a suitable antenna size for implementation on picosatellite structure. Furthermore, the chosen antenna needs to exhibit suitable polarization to ensure the achievement of the desired performance even when designed in a compact size. In view of these challenges, antennas chosen to fulfill the requirements of picosatellites are expected to be rather distinct

compared to those implemented on conventional satellites. Their requirements and parameters are stated in the sections below, while an overview of the different picosatellite antennas is summarized in Table 2.

Operating Frequency. There has been yet a series of standardized operating frequency for CubeSat's communication system. The early development of the CubeSat involved the use of amateur radio frequencies in the VHF and UHF bands due to its low cost and high accessibility by the end users involved in the development of the first CubeSat [1]. UHF and VHF band were also chosen as the frequency specifically for telemetry, tracking, and command (TT&C) in CubeSats [33]. After several years since the first launch of the CubeSat, various antennas have been developed at different operational frequencies depending on their requirements and applications. The wide use of the UHF and VHF bands for data and voice communications was also demonstrated by the TURK-SAT CubeSat project. The antenna system development is divided into two parts. The first system is a receiver part consisting of quarter wavelength dipole antennas with a width of 3 mm and a length of 50 cm operating at 145 MHz. Meanwhile, the second section is a trifunctional transmitter antenna, for the downlink of the beacon, modems, and transponders. This antenna operates at 435 MHz and consists of six-quarter wavelength dipoles similar to the receiver antenna. Hence, the total ten antennas used for the UHF and VHF bands in this project increased the system's cost and complexity [34].

Meanwhile, an S-band antenna for CubeSat was developed by team from MIT using the inflatable antenna concept. This antenna operating at 2.45 GHz with a 10 dB gain is developed for the purpose of extending the exploration into Geostationary Earth Orbit (GEO) from LEO [35]. A reflector was added in the antenna structure for improved gain performance [36], which consequently resulted in the achievement of a high communication data rate [35]. This then extended the distance of the system from LEO to GEO in [36].

Besides UHF, VHF, and S-band, a CubeSat with Ka-band operating frequency for radar applications has been introduced for deep space research by NASA. The antenna was designed in an umbrella-like reflector form and the feed horn placed at the center of the antenna as shown in Figure 1. The operating frequency is at 34 GHz with a gain of 42.8 dBi [37].

ii) Circular Polarization. Besides the need to exhibit high gains at the target operating frequency, the polarization of a CubeSat antenna is also of importance. Circular polarized (CP) antennas are typically used in various applications of satellite communication due to its ability to receive randomly polarized signals better than a linearly polarized antenna. This is advantageous for long distance communication between a satellite and a ground station.

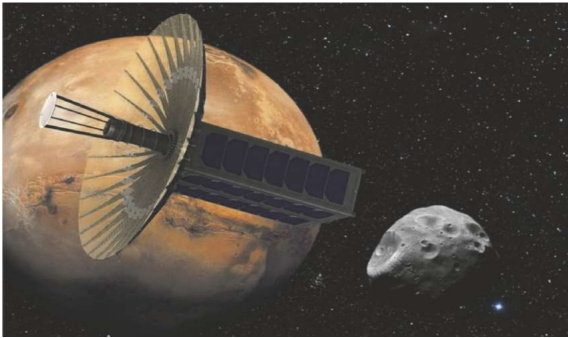


FIGURE 1: A CubeSat with Ka-band reflector antenna for deep space mission [37].

However, the design of such high gain, broadband, and directive circularly polarized antenna is challenging. One of the antenna prototypes which meets such requirements is proposed in [38], with a wide impedance bandwidth of 50.2% and 27% of axial ratio bandwidth. Meanwhile, the designs proposed in [39, 40] produced a wide 3-dB axial ratio beamwidth higher than 120°. Besides that, a high gain circularly polarized antenna investigated in [41] exhibited a gain of more than 10 dBi.

A more sophisticated circularly polarized antenna design was enabled via the sequential phase feeding technique [39]. More than 10% of impedance bandwidth was produced with a high axial ratio bandwidth with a reasonably miniature form on a Rogers RO4003D substrate; see Figure 2 [39]. This substrate features a relative permittivity of 3.55 and a thickness of 0.813 mm, enabling the antenna operation at 1.6 GHz [39]. The design consists of two pairs of complementary dipole antennas located parallel to each other on a square shaped substrate. As shown in Figure 2(a), each dipole is connected to a phase shifter centered on the substrate. Each arm is designed with a 90° phase difference to feed the circularly polarized antenna. The four striplines were combined with a patch to form a balun, enabling the dipole to operate in a balanced mode, as shown in Figure 2(b). The final structure exhibited a 10 dB bandwidth of about 31% and a 3-dB axial ratio bandwidth of 1.6%, with a peak gain around 5 dBi [39].

Another technique to provide high gain and wide bandwidth for circularly polarized antennas is by sequentially rotating the feed to enable circular polarization and increase gains [42–45]. This technique can be generally implemented using a number of identical radiating elements, which are fed sequentially using a 90° phase difference to enable bore-sight circular polarization. For instance, the design in [42] consists of four sequentially rotated circular slot antennas (in a 2 × 2 configuration) and a sequentially rotated feed network. The circular feed network is chosen to minimize discontinuity between the feed, with each arm placed perpendicular to each other to generate circular polarization by adapting the 90° rotating technique. The final design indicated significant improvements; the single antenna gain of 3.6 dBi is improved to be 8.7 dBi for the array with

TABLE 2: An overview of the different picosatellite antennas from literature.

Antenna model	Deployable (yes/no)	Frequency band	Size dimension	Stow size/location	Stow-to-deployment ratio	Gain	Ref
	No	V-band (60 GHz)	10 cm × 10 cm × 0.32 cm	NA	NA	15.4 dBi	[57]
	Yes	Ka-band (26 GHz)	33.9 cm × 8.26 cm	On chassis	1:1	33.5 dBi	[72, 73]
	Yes	X-band (8.425 GHz)	3.3 cm × 19.9 cm	On chassis	1:1.1	28 dBi	[73]

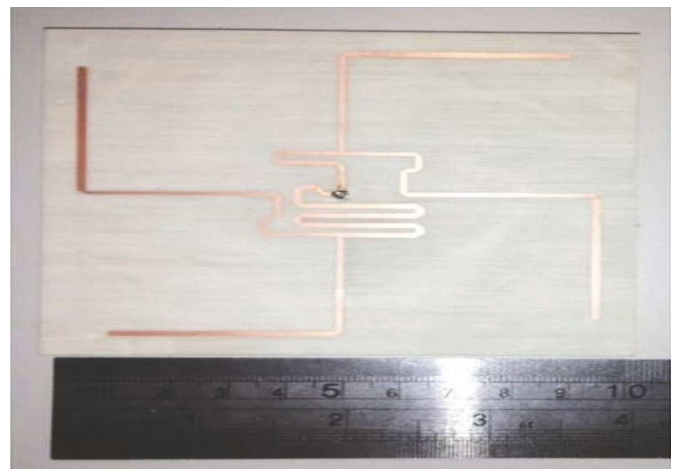


FIGURE 2: CP antenna with phase shifter. (a) Front view and rear view [39].



FIGURE 3: Compact antenna with symmetrical slit [46]. an impedance bandwidth of 3.8 GHz, operating from 4.2 to 8 GHz [42]. In comparison, a wider impedance

bandwidth of 6.2 GHz (between 4.8 and 11 GHz) is exhibited by the single element antenna. However, its 3 dB axial ratio bandwidth is approximately 1 GHz in contrast to 1.9 GHz

for the antenna array [42]. Similarly, the circular polarized antenna described in [45] consists of four identical rectangular patches and feed networks located on the top and bottom surface of a substrate respectively, with an overall size of 10×10 cm². Each patch is placed orthogonally on each side of a square ring. A 90° phase difference between the two orthogonal pairs of patches produced by the feeding network enabled circular polarization at boresight [45]. This feeding network is typically designed using quarter-wave transformers adapting the Wilkinson power divider structure. Each patch is fed equally from the feeding network after the input power is divided using three power dividers. The antenna operates at 2.45 GHz with a gain of 5.9 dBi for a single patch element, which is improved to 7.3 dBi for the complete structure, with a near-to-one axial ratio.

Circular polarized antenna could also be implemented on a single patch antenna by applying elements on its surface such as truncation, slot, or parasitic elements. An example is shown in Figure 3 where a microstrip antenna with several additional splits on each corner of the antenna to enable

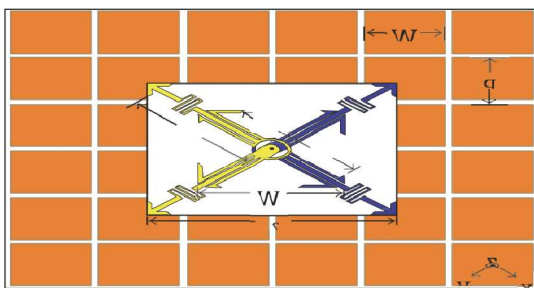


FIGURE 4: The illustration of the compact circular polarized crossed dipole antenna with high impedance surface (HIS) on the back of the antenna [48].

circular polarization with a compact size [46]. Comparison of the same antenna on two different substrates, FR-4 and Rogers RO4003C, shows that the latter performs better compared to FR-4 substrate in terms of gain without any size changes. The FR-4 impedance bandwidth was 3.85% with a 3- dB axial ratio bandwidth of 1.5% and a peak gain of 0.8 dBic. Meanwhile, the antenna on Rogers RO4003C resulted in an impedance bandwidth of 1.5% and an axial ratio bandwidth of 0.5% and a peak gain of 3.4 dBic [46], indicating that the substrate significantly influences the resulting gain.

Another method to create circular polarization is by using crossed dipole antenna fed with an equal amplitude but 90° of phase difference [47–50]. The dipole illustrated in Figure 4 is composed of delay lines with a 90° phase difference. This structure is centered on the antenna design to form a ring shape. Both parts of the dipole antenna were crossed between a ring at the center and fed by a 50 Ω

coaxial cable [47, 48]. The dipole on the top and bottom side of the substrate is connected with the inner

and outer layer of coaxial cable, respectively [47, 48]. With some modification on the dipole structure, a circular polarization was exhibited by this design with an axial ratio less than 3 dB [47, 48].

III. CONCLUSIONS AND FUTURE PERSPECTIVES

This paper presents the review of antennas for picosatellites, including its applications and requirements and mechanism for deployment. Current applications for CubeSat include its use for observation, communication, education, and research, while its usage in other segments is still currently being studied. Its relatively short development time and cost efficiency are the attractive features which motivated its increasing popularity. Due to the nonstandard operating frequency, small available area, high gain, and circular polarization requirements, designing a CubeSat antenna is relatively challenging. Due to this, deployable antennas are becoming more of a necessity due to the electrical length at lower VHF/UHF bands and enhancing gain in the S- and V-bands. Due to this, deployable antenna must consider materials which are flexible and robust for operation in space. Issues in deployment such as the rigidity of the mechanical support structures, accuracy of the deployment, storage-to-deployment size ratio, and maintenance of the inflation rate need to be addressed in future investigations. In recent years, frequency bands used for picosatellites are moving towards higher frequencies (Ka-band, V-band) for size reduction of radio frequency (RF) payloads and to cater for higher speed data downlink. As a result, there is an intensive development of high such gain Ka-band antennas for picosatellites such as in the University of California, Los Angeles (UCLA) and the University of Kent, UK. Moreover, additional features for picosatellite antennas such as electronic beam steerable smart antennas will be employed for high-speed and power efficient data downlink and intersatellite wireless links. These compact-size low-power smart antennas will replace fixed-beam antennas currently in use and make future wireless systems more power efficient and flexible. Besides that, novel materials, components, and fabrication technologies will enable better performing picosatellites antennas at lower costs, such as 3D printing [80]. A number of established antenna models employing such 3D printing method are already proposed in [80–81]. Besides 3D printing technology, chip satellites and satellite-on-chip, and antennas on chip for such chip satellites are among other developments for future picosatellite technology, especially for CubeSat applications. Clearly, intersatellite links will be important for constellations of

picosatellites, which requires the use of either multiple high gain antennas or antennas with beam switching and diversity techniques. More details of the state-of-the-art development for CubeSat antennas are also provided in [82].

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