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Antenna Designs for Amateur Band Low Earth Orbit (LEO) Satellites – A Review

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Abstract : CubeSat has been widely developed for various purposes, including scientific, private and government missions. This paper shows various cube satellite antenna design techniques. The antennas used in miniaturized satellites have undergone a multitude of changes from a monopole antenna till use of small micro strip patch antennas. This survey lists out the various advantages and disadvantages of each and every antenna designs that were proposed for CubeSat use over time. One of the major issues in antenna design lies in the antenna deployment. Any disaster during the deployment will lead to failure of the entire mission due to malfunctioning in implementing a communication link between the CubeSat and a ground control system. This paper discusses the multitude of designs proposed for the antenna fabrication in order to achieve excellent performance, high gain, high stability and reliability, as well as low-profile, compact dimensions.

Keywords - CubeSat, picosatellite, nanosatellite, antenna, micro strip patch antenna, miniaturized antenna, antenna gain.

I. INTRODUCTION

A CubeSat is a small satellite that is based upon a standardized specification. The original CubeSat, known as 1U or 1 Unit, is a 10cm cube with a mass less than 1.33kg.The most common sizes are 1U,2U and 3U, while sizes upto 27U are being developed[10].CubeSats are used in the areas of scientific research, technological demonstration and commercial applications. The capability of a CubeSat in terms of scientific measurements and performance of communications systems are limited compared to large satellites, due to the restricted volume and power availability. One of the key sub-systems of every satellite is the communication system. About 17% of satellites failed due to communication system failure [3]. This communication system ensures the data transmission between the satellite and the ground station. In communication system, the design of an antenna plays a major role. The CubeSat is made to operate in Very High Frequency/Ultra High Frequency or S band especially in amateur bands using a monopole, dipole or patch antenna [3].

The type of antennas that are designed for a particular CubeSat depends upon its frequency of operation. The design proposed by [1, 8, 11, 12] deals with the antennas intended for working in UHF, VHF frequencies. The design proposed by [1, 4, 8] deals with inflatable antenna working around 2.4 GHz. In papers [8,13], the design of helical antenna is recommended to work over a wide range of frequencies ranging from 400 MHz over 60 GHz. The papers [2, 5, 7, and 8, 9, 12] discuss patch antennas that operate in ultra-high frequency bands and in S band.

II. CUBESAT ANTENNA APPROACHES

In accordance to the standard design requirements different solutions have been proposed in different universities, pursuing an evolution, aiming for higher data rate. The different approaches considered for space exploration are described on the following subsections, but as a starter, considering the Table 1.

2.1 Dipole Antenna or Wire antenna

In Teresa et.al, centrally fed dipole antenna was proposed for CubeSat. The length of the radiating element determines many of the properties of the antenna like impedance, working frequency, radiation pattern, etc. Historically, the λ/2 dipole is one of the most used by amateurs worldwide because of it ease to build and its effective performance. A dipole can be either fed centrally or energy can be fed into a dipole either by using a central feed or an off-set feed system. The omni-directionality of the antenna provides wide signal coverage, especially when the CubeSat operates in the UHF band [1].On the other hand Abdul et.al, to cater to the limited space in CubeSats, most developers has tried to maintain the use of a single antenna to achieve simplicity and avoid the use of deployment mechanisms. However

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several researchers have also implemented simple monopole antennas as shown in Fig.1, which are deployed using tape spring method [8].It is one of the earliest methods adapted in CubeSat .A mono filament was used to hold the antenna using a small nichrome wire which is heated by a small amount of current produced inside the CubeSat.[8].However, such antennas are found to be limited in terms of gain and result in large size that is not practical for CubeSat when using conventional designs. Moreover their omni-directional radiation behavior may not be suitable for all applications, especially in cases requiring high directionality [1].

Table 1: Evolution of antennas for CubeSat [1]

MISSION	SUPPORT	ESTIMATED LIFE SPAN	ANTENNA DEVELOPMENT	ANTENNA TYPE	WORKING FREQUENCY
AAU1 CubeSat	Aalborg University (Denmark)	3 months	Commercial from OSS	Dipole	437.425 MHz (Half Duplex)
DTUsat-1	Technical University (Denmark)	6 Months	Designed at University	Canted Turnstile (Half Duplex)	437.475 MHz (Half Duplex)
Andusat-1	Kickstart	2+ months	Commercial from Gom Space (5.550C)	Turnstile Antenna	437.325 MHz (Half Duplex)
Vermont Lunar Cube	Vermont Technical College (USA)	1+ months	Commercial from ISIS (4.500C)	Cross Dipoles	DL: 437.305 MHz UL : 150 MHz
BEESAT 1	Technical University of Berlin (Germany)	43+ months	Designed at University	Quarter wave monopole antenna with toroidal radiation pattern	436 MHz (Half Duplex)
BEESAT 2		2+ weeks		2x monopole	435.95 MHz (Half Duplex)
BEESAT 3		2+ weeks		UHF monopole and 5 patch antenna	DL : 435.95 MHz UL: 2.263 MHz

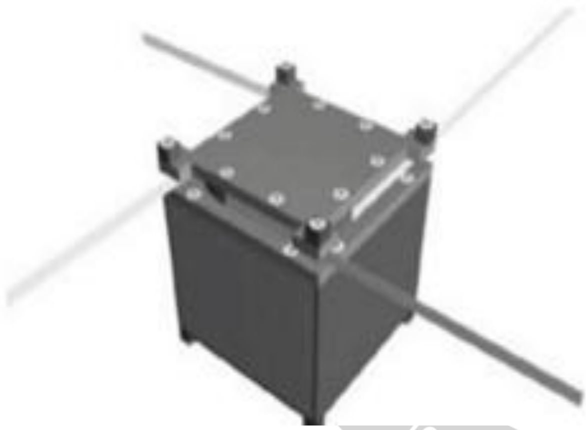
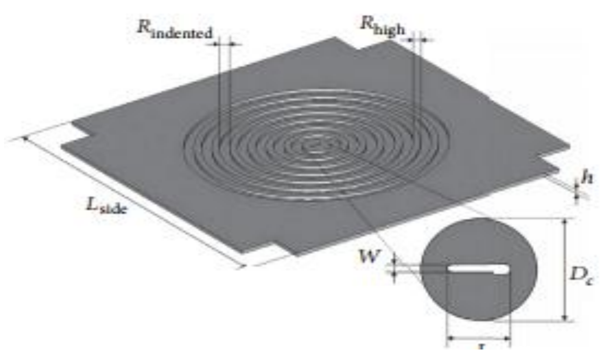


Fig.1.Deployable antenna on 1U CubeSat

2.2 Reflector or Inflatable Antenna



According to Alessendra et.al, a 1 m inflatable antenna is designed to operate in the S-Band (2.4 GHz). The inflatable antenna shown in fig.2, uses a sublimating powder like benzoic acid instead of gas stored in pressurized tanks to operate under full pressure for over a year. The reflective, aluminized Mylar used in these prototypes is 0.0002" (512 μm) thick, and the clear Mylar is 0.0001" (256 μm) thick. The parabolic reflector is formed by first cutting petal-shaped patterns which are mathematically designed and the edges are joined together. Leakage along the joints can significantly affect the antenna performance.

For inflatable antenna, it is necessary to ensure that the antenna can be folded and stored in the CubeSat occupying a limited volume. Specifically, the antenna needs to occupy less than 0.6U of CubeSat, a feasible communication solution for a 3U mission [4]. Inflatable antennas are preferred to maintain high gain.

The main disadvantage in inflatable antenna is ensuring the retention of the shape of the antenna after deployment. Also leakage loss in the membrane and the wrinkling of the material affect the radiation characteristic of the antenna [4].

2.3 Spiral/Helical Antenna

According to Abdul et.al, one type of spiral antenna known as the "Bull's Eye" antenna which consists of several circular rings of different diameters as shown in Fig.3. The smallest ring with a diameter of 7.12 mm is located at the center of this structure and surrounded by another seven larger rings indented on a 3.2 mm thick aluminum plate to operate at 60 GHz for 59 GHz to 71 GHz inter-satellite communication. The overall size of the antenna is 10 mm^2, and additional incisions of 10mm^2 are introduced at each

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corner of the square shaped antenna to fix with the CubeSat chassis[8].

Besides rings, helical antennas operating in the UHF band has also been introduced for use on CubeSats. Its operation at 400 MHz results in a relatively large antenna compared to other high gain antennas of CubeSats. During storage, the antenna was folded and rolled into a small structure and is deployed using the stored strain energy. A gain of 13dBi and an axial ratio bandwidth of about 55% are exhibited.

The main problem encountered in the spiral antenna is the requirement of compact folding in order to achieve high package ratio gain during launch [8].

Fig. 2.Conical and cylindrical configurations of Inflatable antenna [4]

III. PATCH ANTENNA

According to Anitha et.al, Microstrip patch antennas (MPAs) have gained a widespread interest due to their small size, light weight, low profile and low cost, simple to manufacture, suitable to planar and non-planar surfaces, mechanically robust, easily integrated with circuits, allow multi frequency operation. Wide bandwidth of microstrip patch antennas (MPA) or bandwidth enhancement can be achieved by several efficient methods[9] , namely (i) increasing the thickness of the substrate (ii) optimizing impedance matching (iii) reducing the effective permittivity of the substrate or (iv) incorporating multiple resonance.

In this paper, coaxial feed techniques are applied to the square microstrip patch antenna. The inner conductor of coaxial cable is connected to the radiating patch and the outer conductor is connected to the ground plane. This feed is also easy to match, and it has low spurious radiation. However, it has a narrow bandwidth and is difficult to model, especially for very thick substrates. The main advantage of this feed is that it occupies less space when compared with the other feeds.

A microstrip line has a single ground plane and a thin strip conductor placed on a low loss dielectric substrate which is above the ground plate [9]. Due to the absence of the top ground plate and the dielectric substrate above the strip, the electric field lines remain partially in the air and partially in the lower dielectric substrate. This makes the mode of propagation not pure TEM and it is called quasi-TEM. Due to the open structure and presence of discontinuity, the microstrip line radiates electromagnetic energy. The use of thin and high dielectric materials reduces the radiation loss of the open structure where the fields are mostly confined inside the dielectric.

Coaxial and parallel wire transmission line employ TEM mode. In this mode the electromagnetic field lines are contained entirely within the dielectric between the lines. But the microstrip structure causes an abrupt dielectric interface between the substrate and the air above it. Any transmission line system which is filled with a uniform dielectric can support a single well defined mode of propagation at least over a specific range of frequencies (TEM for coaxial lines TE or TM for wave guides). Transmission lines which do not have such a uniform dielectric filling cannot support a single mode of propagation. Here the bulk of energy is transmitted along the microstrip with a field distribution which quite closely resembles TEM and is known as Quasi – TEM.

3.1 Design principles

The first step in the design is to specify the dimensions of a single microstrip patch antenna. The patch conductor can be assumed at any shape, but generally simple geometries are used, and this simplifies the analysis and performance prediction. Here, the half-wavelength rectangular patch element is chosen as the array element (as commonly used in microstrip antennas). Its characteristic parameters are the length L, the width w, and the thickness h.

$$L = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}} - 2\Delta l$$

Where c is the velocity of light and

$$\Delta l = 0.412 \times h \times \frac{(\varepsilon_{eff} + 0.03)\times(w + 0.264h)}{(\varepsilon_{eff} - 0.258)\times(w + 0.8h)}$$

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$$\varepsilon_{eff} = \frac{\varepsilon_{r+1}}{2} + \frac{\varepsilon_{r-1}}{2} \times \left(1 + \left(\frac{12h}{w}\right)\right)^{\frac{-1}{2}}$$

Here, ε_{eff} and fo, Δl are effective relative permittivity, the operating frequency, and the fringe factor respectively.

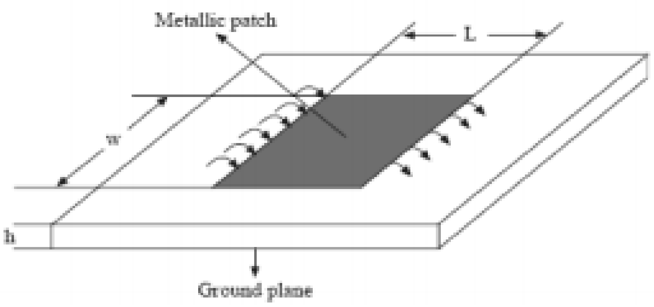

Fig.4. A Rectangular Patch antenna

From these approximate calculations, the dimensions of the square-shaped microstrip patch antenna element are specified as shown in Fig 2. For a linear array with a uniform excitation, the beam width is given by,

$$\theta_{3db} = cos^{-1}[sin(\theta_0) - 0.443\frac{\lambda_0}{l}] - \cos^{-1}[\sin(\theta_0) + 0.443\frac{\lambda_0}{l}]$$

Where θo is the main beam pointing angle, λ_0 is the free-space wavelength, and l is the total array length. The dimensions are w = 7.6 cm, h = 3.175mm, ε_r = 2.2 and a = 9.5 cm.

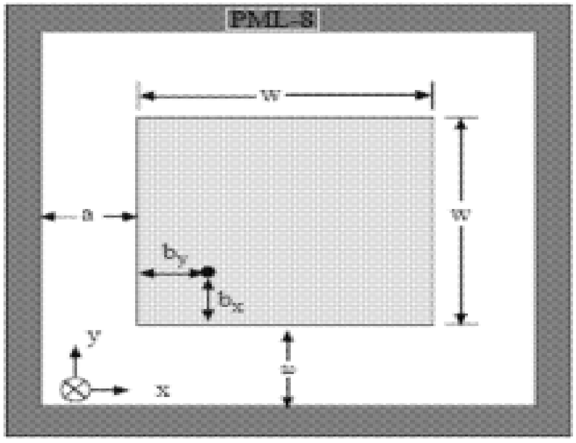

Fig.5. The square Patch Element

IV. DIFFERENT PATCH ANTENNA DESIGNS

A patch antenna is widely used due their compact size and robust nature. They have the capability to be easily etched on any PCB and will also provide easy access for troubleshooting during design and development.A patch antenna is capable of supporting multiple frequency bands (dual, triple). They are also capable of being designed to operate over a large frequency band (MHz to GHz). Thus patch antenna becomes a suitable alternative for implementation in CubeSats.

4.1 Shorted Patch Antenna

Shorted patch antenna was discussed by FaissalTubbel[2]. It has two patches 18×15 mm^2 upper patch and 7.5×6.5 mm^2 lower patch. They are connected to a 30×30 mm^2 ground plane via four shorting pins and a probe feed. The main use of the shorting pins at the edge of the upper patch is to achieve miniaturization at wide BW[2]. The center shorting pin is used to enhance the impedance bandwidth of the shorted patch antenna by generating another two resonant frequencies of 4.45 and 7 GHz.

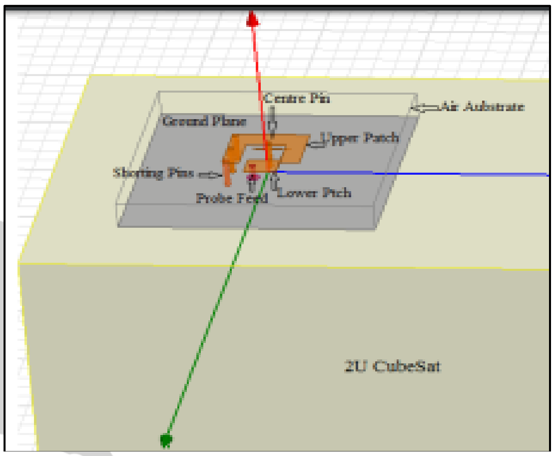

Fig. 6. Geometry of shorted patch antenna on 2U CubeSat [2]

In order to shift the frequency of position of the antenna to 2.4GHz, the physical size of the patch antenna is increased from 30x30 mm^2 to 83x83 mm^2. This re-dimensioning allows the short patch antenna to have a high gain and operating with a wider bandwidth.

4.2 CPW-feed Square Slot Antenna

From the Faissal Tubbel [2] et.al, a distance (air gap) between the antenna and the satellite body is provided to prevent any contact between the back side (dielectric) of the antenna and the surface of the satellite body. This decreases the capacitance between the upper ground plane and the CubeSat body and leads to higher gains. The CPW-feed square slot antenna has a total size of 60×60 mm and it is fabricated on FR4 substrate which has a thickness of 0.8mm. Coplanar Wave Guide (CPW) feed line technique is used with a fixed width of a single strip; i.e., 4.2 mm and the distance between the line and ground plane is 0.3 mm in order to achieve 50 Ω matching[2].

In addition, the CPW-feed square slot antenna operates at 3.2 and 9.1 GHz. Its first operating frequency 3.2 GHz is shifted to 2.45 GHz (S-band) by re-dimensioning the entire antenna parameters. Quasi Newton optimization method is used for the re-dimensioning process to achieve an operating frequency of 2.45 GHz. The antenna size is increased by 1.25 mm and has achieved a return loss S11 of -25 dB at an operating frequency of 2.45 GHz.

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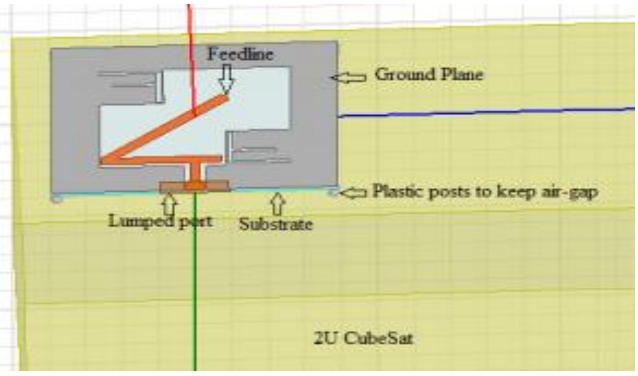

Fig.7. Geometry of CPW-feed square slot antenna on 2U CubeSat[2]

The operating frequency of the antenna is shifted by increasing the size of the patch antenna based on quasi Newton method. This increase in size results in the minimum return loss at 2.4GHz. The variation of the size is made from 60x60 mm2 to 75x75 mm^2. In order to improve the gain of the re-dimensioned CPW feed square slot antenna, the F shaped slit are replaced by square slots in a design. This decreases the bandwidth but it is still wide enough for CubeSat communication. [2].

V. DUAL FEED, DUAL BAND STACKED ANTENNA

According to Yeleiyao, the dual-band antenna system is mounted on the nadir-facing side (100 mm × 100 mm) of the CubeSat. The antenna system is formed by three layers, nevertheless keeping a low profile of 11 mm and a weight of less than 120 g, which is suitable for the CubeSat. The top layer is the upper patch antenna, the middle layer is the lower patch antenna, and the bottom layer is the metallic ground with the embedded feeding network. The lower patch antenna serves as the ground of the top antenna. The network is achieved by two independent 3-dB branch-line hybrid couplers using striplines instead of microstrip lines for a compact and low profile as well as to keep the feeding network from electromagnetic interference and other disturbances [7].

This study uses dual-feed technology, more specifically, two independent 3-dB branch-line hybrid couplers, to feed the lower and upper band antennas, respectively. This method allows for more stable and wider-band AR performance compared with a single-feed method.

The feeding positions of each patch are located orthogonally and at the same distance with respect to the antenna center. Each patch antenna is excited by two-way signals with equal amplitudes and a 90° phase shift during the simulation.

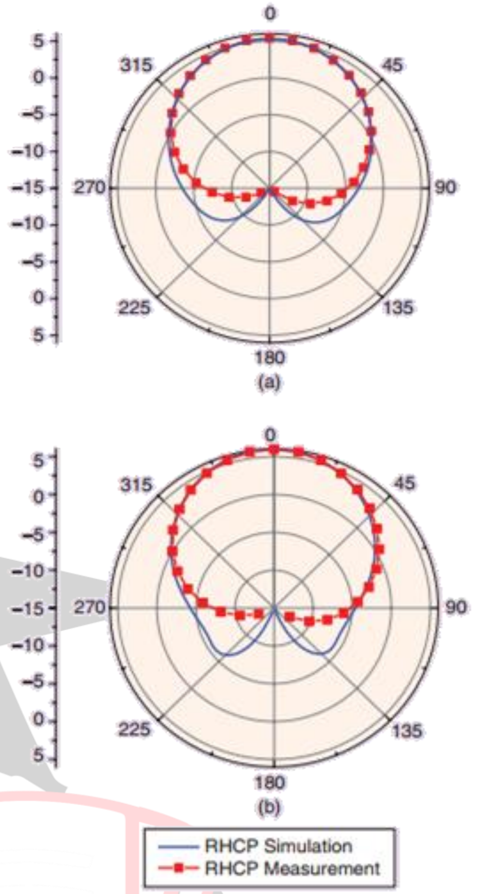

Fig.8. The measured and simulated radiation pattern results of the dual frequency bands in x-z plane[7]

The antenna configuration has the capability to be tuned to a slightly lower frequency and adjust it to the desired frequency by cutting the four stub shorter and shorter. The antenna proposed in this article demonstrates excellent performance, high stability, reliability and low profile [7].

VI. DESIGN OF PATCH ANTENNA FOR UHF BAND

In Prem Sundaramoorthy et.al [12], the patch antenna for the use in UHF band is proposed either by using a substrate of very high dielectric constant or by employing a fractal antenna to fit in a CubeSat. The PIFA (Planar Inverted F Antenna) is a type of antenna where the patch is short circuited via the strip to the ground thus allowing the antenna to resonate to the smaller antenna size when compared to the regular patch antennas [12].

The main benefit of this antenna is the absence of deployment mechanism. This greatly increases the reliability of the antenna. The absence of electronics necessary to command the deployment system makes the PIFA have lower power consumption. This antenna operates in UHF frequencies instead of S band frequencies.

VII. CONCLUSION

From the references reviewed above, it is observed that the deployment mechanism can lead to a high probability of

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failure of the entire CubeSat, if not implemented properly during the satellite's deployment in space. Unlike traditional wire antennas, the micro-strip patch antennas do not require deployment mechanisms; Instead, these antennas can be permanently fixed on, one face of the CubeSat, which is looking towards earth. There is no patch-antenna available as of yet, capable of operating in the amateur band without deployment mechanisms. Thus, this paper consolidates all the available antenna designs with all their merits and demerits. Thus our research will be focused on design of a micro-strip patch antenna operating at VHF/UHF frequencies, in the size of 100mm x 100mm, which is comfortably fit in CubeSat.

Table 2: Comparison of antennas used in Amateur band LEO Satellites

AUTHOR	ANTENNA	FREQUENCY OF OPERATION	ADVANTAGE	DISADVANTAGE
Teresa et.al	Wire Antenna	UHF and VHF band	Simple to design, wide signal coverage	Requires the need for deployment can cause ultimate failure, for higher frequencies size of antenna becomes very large
Alessendra et.al	Inflatable antenna	Around 2.4 GHz	Can be made to fit into very small CubeSats	Shape retention of the antenna is problematic, leakage losses
FaissalTubbel et.al	Shorted patch antenna	4.45 to 7 GHz	High gain and wide bandwidth, high performance	Low power handling capability, radiation loss from shorted pins
FaissalTubbel et.al	CPW feed antenna	3.2 to 9.1 GHz	Low profile antenna, low dispersion, simple realisation	Bandwidth decreases with redimensioning, costly, requirement of thick substrate
Yeleiyao et.al	Dual stack patch antenna	L and S band	High performance high stability and reliability, tunability	Expensive to fabricate and complex design

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