Comparison of the communication time of a high gain versus a low gain monopole-like low profile antenna on a 3-unit CubeSat

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***Abstract*— This paper investigates the effect of the antenna pattern on the communication time between a ground station and a low earth orbit satellite with passive attitude control, i.e. the antenna is nadir pointing. Two low profile antennas that fit on a 3-unit CubeSat are considered, namely a high gain patch and a low gain monopole-like patch antenna. The communication system is for high speed S-band communication.**

Keywords-CubeSat; patch antenna; satellite communication

I. INTRODUCTION

A number of universities are using small satellites, specifically CubeSats, as a platform for space research [1]. A CubeSat is a nano-satellite that adheres to the CubeSat standard compiled by the Stanford University and California Polytechnic State University [2]. This standard specifies a rapid and low cost development satellite that makes use of commercial off-the-shelf components. In this research a 3-unit CubeSat is considered. As antennas on the satellite need to conform to the Poly-Picosatellite Orbital Deployer (P-POD) dimensional restrictions [3], the antennas have to be of low profile if no deployment mechanism, which increases the required antenna space in the satellite and increases risk, is considered.

Due to their size, weight and power budget restrictions, CubeSats typically have little or no attitude control. For low earth orbit satellites aerodynamic drag torques together with a magnetic damping mechanism can be used for rough attitude stabilisation [4]. In [5] this concept was used on a 3-unit CubeSat and this attitude control system is also used in this research. It is thus assumed that the satellite has a circular orbit at a height of 600 km (this is the worst case scenario, ideally the satellite should be in a lower orbit to increase the effectiveness of the passive aerodynamic system) and the antenna is nadir pointing.

For this system an ideal antenna pattern would be dependent on the orbital height and the satellite elevation angle. The gain would be at a minimum at zenith and needs to gradually increase to a maximum at the horizon according to an R_d^2 law, where R_d is the slant range between the ground station and the satellite. A minimum antenna gain of -7 dBi is required, according to the link margin calculation of the communication system, when the satellite is at zenith relative to the ground station. The relationship between the slant range, R_d, and the elevation angle, ε, the nadir angle, α, and the earth coverage angle, θ_e, are given in equations (1) through (3) respectively, and are illustrated in Figure 1. Here it is assumed that the ground station height is zero. The satellite height above ground is h_{sat} and the earth's radius is R_e.

$$R_d = \sqrt{(R_e + h_{sat})^2 - R_e^2 \cos^2(\varepsilon)} - R_e \sin(\varepsilon), \tag{1}$$

$$R_d = (R_e + h_{sat})\cos(\alpha) - \sqrt{R_e^2 - (R_e + h_{sat})^2 \sin^2(\alpha)}, \tag{2}$$

$$R_d^2 = R_e^2 + (R_e + h_{sat})^2 - 2R_e(R_e + h_{sat})\cos(\theta_e). \tag{3}$$

Figure 2 defines the variables and illustrates how the required antenna gain varies with the satellite at various elevation angles.

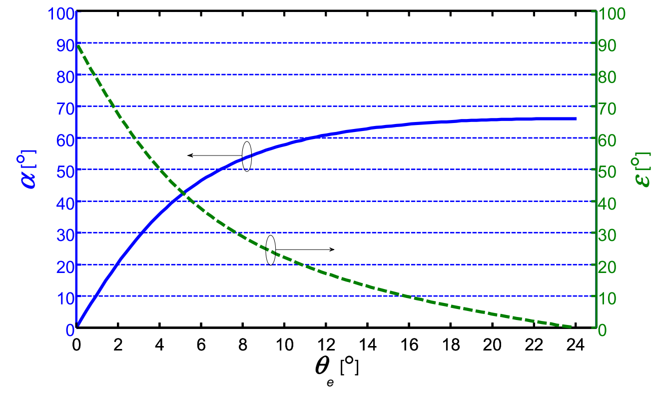

Figure 1: Relationship between the elevation angle, ε, the nadir angle, α, and the earth coverage angle, θ_e, for a satellite at 600 km.

Table I shows how the slant range varies from horizon ($\varepsilon = 0°$) to zenith ($\varepsilon = 90°$). Also shown in Table I are the

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satellite nadir angle and the path loss variation. The path loss column shows that for a satellite in a 600 km orbit, the required gain variation from zenith to horizon is 13.5 dB. From the antenna point of view, i.e. the nadir angle, *α*, this means that the antenna must have its maximum gain at 66.1° and minimum at 0°. This translates to an antenna beam coverage of 132.1°. The required gain profile relative to the ground station and the slant range are illustrated in Figure 3.

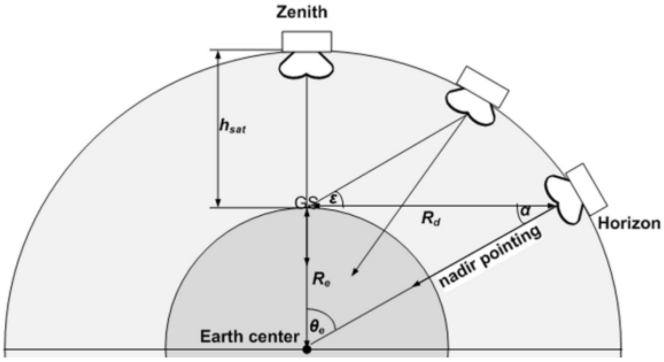


Figure 2: Illustration showing the antenna radiation pattern relative to the ground station.

TABLE I. RELATIONSHIP BETWEEN ORBIT PARAMETERS

Elevation angle, ε [°]	*Slant range, R_d [km]*	*Nadir angle, α [°]*	*Path loss, L [dB]*
0	2831	66.05	169.1
4.2	2400	65.72	167.7
25.4	1200	55.65	161.6
90	600	0	155.6

The optimum antenna radiation pattern is a saddle point shaped radiation pattern, like that of a quadrifilar helix antenna [6-7]. However, this antenna is relatively big and would need some sort of deployment mechanism to be used on a CubeSat.

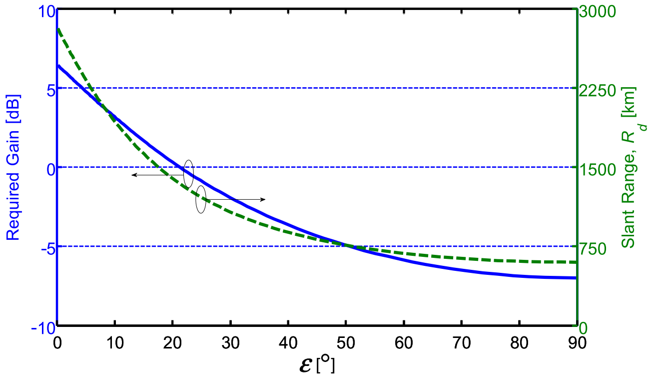


Figure 3: Required antenna gain and slant range versus elevation angle for a satellite at 600 km.

In this paper only single low profile antennas are considered that do not require a deployment mechanism after launch. As such a typical patch antenna that has relatively high gain, i.e. a directional antenna, and a low gain patch antenna that has a monopole-like radiation pattern are considered. In the first case we have good antenna gain when the satellite is at zenith relative to the ground station and it gradually decreases as the satellite's elevation angle is closer to the horizon. In the second case there will be no communication at zenith due to the null in the monopole radiation pattern, but the gain increases as the satellite's elevation angle decreases towards the horizon. The full wave electromagnetic simulations take into account the fact that the size of the antenna's ground plane is limited by the CubeSat body. All computational electromagnetic simulations were done with the commercially available code FEKO [8]. In Section II the design of these two antennas is discussed and in Section III the communication time for these two antennas is evaluated. Section IV is the conclusion.

II. ANTENNA DESIGN

Mechanically, the two antennas are similar. They both have a circular metal patch that is supported by metallic pins of which one is the feed pin. No dielectric is used. The feed is terminated in a sub-miniature type A (SMA) connector. In order to ensure a symmetrical antenna pattern, the patch is centred on one of the long faces of the CubeSat as shown in Figure 4. The required frequency band of the communication system is 2.4 to 2.45 GHz.

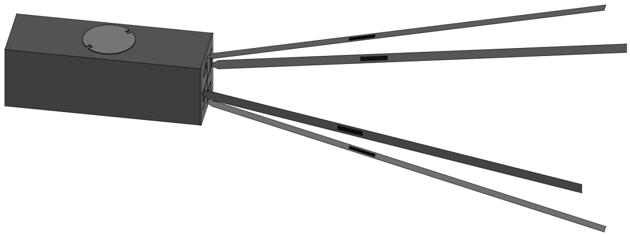
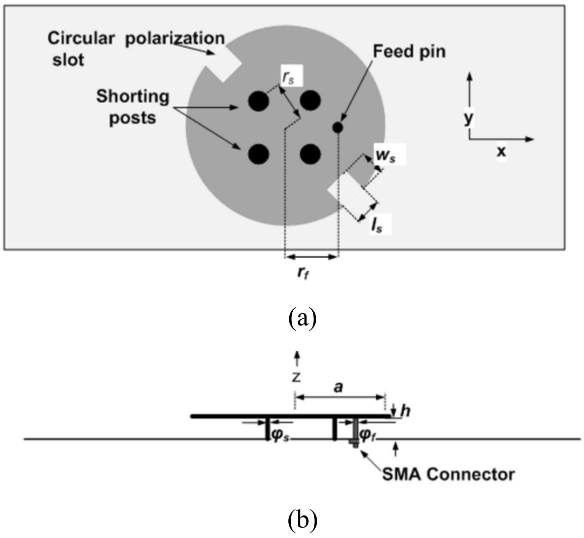


Figure 4: FEKO model of the high gain patch on the 3-unit CubeSat.

A. High gain patch antenna

The cross-section view of the all-metal high gain patch antenna is shown in Figure 5. It consists of a metal plate suspended by four shorting pins, with diameters φ_s, which are located symmetrically a distance r_s from the centre of the circular patch. The coaxial feed location, with diameter φ_f, is on the x-axis and a distance r_f from the centre of the patch.

The antenna parameters were optimised for maximum gain and low reflection coefficient. For this antenna slots can be introduced, if required, for circular polarisation. The slots have little effect on the antenna pattern, but can be optimised for good axial ratio. The final dimensions of the antenna are given in Table II.



(a)

(b)

Figure 5: Cross-section view of the high gain patch antenna, (a) side view, (b) top view.

TABLE II. HIGH GAIN ANTENNA PARAMETERS

Parameter	*Dimension [mm]*
a	39.2
r_f	18
r_s	19.1
h	2.8
φ_f	1.3
φ_s	0.8
l_s	6.0
w_s	6.2

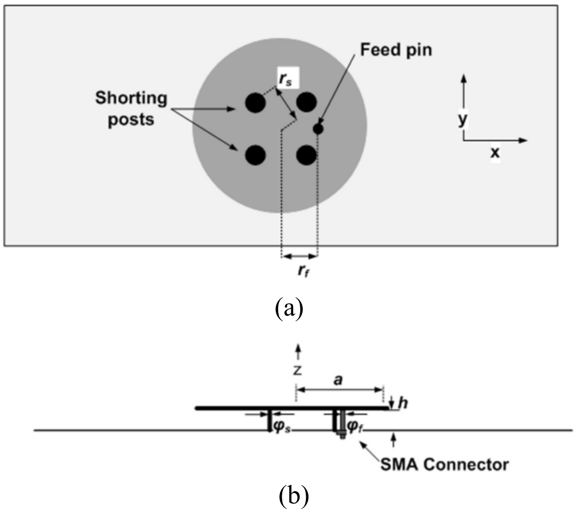
B. *Low gain patch antenna*

The low gain patch antenna is a top-loaded monopole with four shorting pins for impedance matching. The cross-section view is shown in Figure 6. The antenna parameters are equivalent to those of the high gain patch antenna. This antenna is smaller than the high gain antenna, as the patch radius a in this case needs to be smaller than a half wavelength. This antenna can only be linearly polarised.

The antenna parameters were optimised for maximum gain and low reflection coefficient. The final values are given in Table III.

III. PATTERN EVALUATION

Given the antenna designs of Section II, this section evaluates the antennas' radiation pattern in terms of the communication time between the satellite and the ground station.



(a)

(b)

Figure 6: Cross-section view of the low gain patch antenna, (a) side view, (b) top view.

TABLE III. LOW GAIN ANTENNA PARAMETERS

Parameter	*Dimension [mm]*
a	25.8
r_f	12
r_s	19.1
h	5
φ_f	1.3
φ_s	0.8

Figure 7 and Figure 8 show the antenna pattern cuts for the high gain and low gain antennas respectively. These patterns were simulated for the patch antennas mounted on the CubeSat structure. Note that the pattern cuts are plotted against the satellite elevation angle and not the antenna elevation angle. Also shown in these graphs is the minimum antenna gain requirement over the same satellite elevation angles. The antenna gain is required to be above this line in order to satisfy the link margin. The shaded regions indicate where the antenna does not satisfy the required link budget. The maximum antenna gain for the high and low gain patches are 9.8 dBi (at $\varepsilon = 90°$) and 3.8 dBi (at $\varepsilon = 35°$) respectively.

For a satellite with a circular orbit and constant velocity the angular velocity $\dot{\theta}_e$ (as defined in Figure 2) is constant. Taking into account the relationship between the elevation angle, ε, and the earth coverage angle, θ_e, from Figure 1, or equations (1) and (3), it is realised that for most of the time the satellite is at the lower elevation angles. This implies that the antenna should radiate more energy towards the horizon such as is the case with the low gain patch antenna.

The satellite elevation angles for which the antenna gain satisfies the link budget are given in Table IV. From these the visible communication angle, $\Delta\theta_e$, is determined, which is the difference of the elevation angle converted to the earth coverage angle. The maximum satellite visibility angle is $\theta_e = 0°$ to $\theta_e = 47.86°$. The ratio of the visible communication angle to the maximum satellite visibility angle gives the maximum communication time and is given in the last column of Table IV. This, of course, assumes that the satellite flies over the ground station.

The beam efficiency [9] of the high gain patch antenna is higher than that of the low gain patch antenna due to the higher gain which improves on the signal to noise ratio. The beam efficiency is 83.4 %. The low gain patch antenna has low beam efficiency, because some of the radiated energy is transmitted outside the required satellite footprint. In this case the beam efficiency is 47.8 %. The low gain antenna does however perform beter in terms of communication time because of the increased gain for the elevation angles where the slant range between the satellite and the ground station is longer and due to the fact that the satellite spends more time at the lower elevation angles.

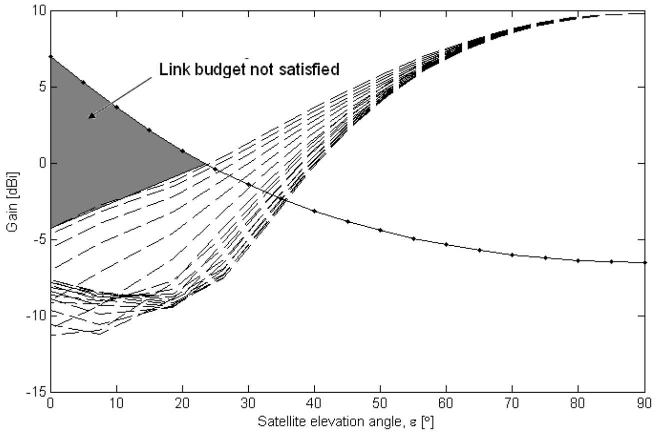


Figure 7: High gain patch antenna pattern cuts (dotted lines) for 19 cuts between $\varphi_{sat} = 0°$ to $90°$, and the minimum gain requirement line (solid line).

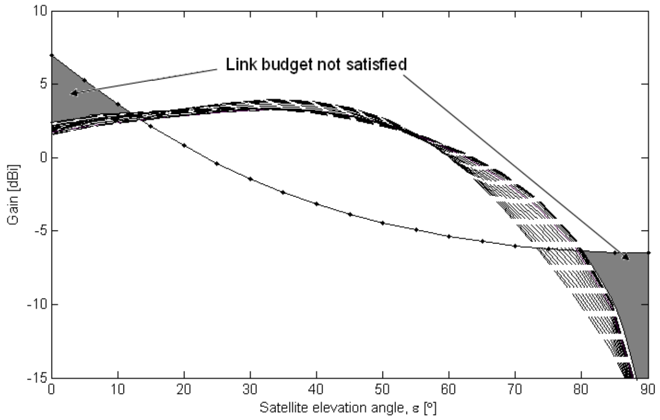


Figure 8: Low gain patch antenna pattern cuts (dotted lines) for 19 cuts between $\varphi_{sat} = 0°$ to $90°$, and the minimum gain requirement line (solid line).

TABLE IV. ANTENNA EVALUATION

Antenna	*Cut*	*Elevation angles, ε [°]*	*Visible Communication angle, Δθ$_e$ [°]*	*Communication Time [%]*
High Gain	Best	24 – 90	9.38	39.2
	Worst	35 – 90	6.53	27.2
Low Gain	Best	12 – 80	13.75	57.45
	Worst	17 – 73	10.56	44.1

IV. CONCLUSION

In this paper the parameters after optimisation of a high gain and a low gain patch antenna are given. From the simulated radiation patterns the communication times were determined. The results show that a low gain antenna with a monopole-like antenna pattern has a longer communication time than a high gain antenna for a nadir pointing antenna on a 3-unit CubeSat.

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