Performance Simulation of a LoRa Low Power WAN CubeSat in Earth Observation Missions

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***Abstract*—Until the last two decades a few superpower countries were the custodian of space exploration by means of satellites. Colossal budgets and expertise required to build and launch a satellite were the major limiting factor. With research making possible space exploration through small satellites, academic institutions boarded the space benchmarking products used in Low Earth Orbits (LEOs) missions. The setup of a satellite system comprising a space segment in a satellite and a ground segment in a transceiver requires the operation frequency band allocation by the International Telecommunication Union (ITU). The acquisition of this frequency band involves administrative procedures and the band license fee, which present a challenge to the seamless space exploration for academic purposes.**

The ground-breaking technology of Tiny Ground Station (TinyGS), which is an open source global satellite network operating with Long Range (LoRa) wireless communication and Internet of Things (IoT) could see the financial and administration hurdles relieved, thus making access to space science by academic institutions. This paper anticipates the performance analysis of a LoRa-Wide Area Network-based cube satellite (cubeSat) under development at a French South African Institute of Technology (FSATI) under the hospices of the Cape Peninsula University of Technology (CPUT). The work presented consists of a simulation of two complementary cubeSats orbiting the earth and sending information to a quarter wavelength monopole antenna through a TinyGS. The results relating to the communication between the cubeSats and the antenna were promising, guaranteeing the implementation of the actual cubeSat system.

Keywords—Cube-Satellite, Lora-WAN, Earth Observation, TinyGS, FSATI

I. INTRODUCTION

The concept of electronic communication of two devices was first introduced in early 1930s by Samuel Morse through electrical telegraph [1]. The objective of this concept was to send text messages among the electronic devices to enhance communication, and this concept was used until the early 20th century. In 1876 Alexander Graham Bell invented the world's first electrical telephone [2], these electric telephones were the first electronic devices that could transmit audible data.

The telecommunication has been one of the fast evolving areas, and this saw satellites being launched in space and being controlled via a ground-based transceiver which serves as means of data collection over the uplink and downlink frequency bands. In the digital era, the information superhighway meant that electronic devices were able to communicate with each other with less delays expected [3].

From the launch of the first satellite in the 1950s, space exploration was a custody of superpowers, for several decades due to unattainable development and launch budgets. In mid 2000s, space exploration research saw a breakthrough with the development of low-cost small satellites. Universities and academic institutions across the world have been hubs for small satellites development for research purposes.

With the advent of the internet technology, the concept of Internet of Things (IoT) was borne and has had influence in our daily life as a primary means for efficient electronic communication. The IoT connection enables devices to send and receive data from each other over the internet without human intervention [4]. IoT plays a big part in space research as it is responsible for sending/receiving data between satellites or ground station while Long Range (LoRa) communication allows long-range using low-power communication between two or more electronic devices. This is a sought-after feature in small satellites that can afford few watts to operate in respect to their small sizes and weight as well as minding that a solar-powered satellite spends the orbit half in the eclipse.

II. WORK DONE ABOUT LORA WAN SATELLITES

The approach in developing a LoRa WAN cubeSat referred to the latest developments in the field of IoTs and TinyGS.

A. LoRa and TinyGS

In Kumar [5], LoRa is a wireless technology that transmits and receives data in the unlicensed Industrial, Scientific and Medical (ISM) band. LoRa Wide Area Network (WAN) is a protocol that can combine LoRa wireless technology into a network [5]. Low Power Wide Area Network (LPWAN) is a wireless network technology that provides low-power, long-range connectivity for IoT devices [5]. LPWAN uses LoRa technology to communicate with IoT, LPWAN is useful to improve inter-satellite communications since it can send data over long distances at a low power consumption [5]. Tiny ground station (TinyGS) is a low-cost and open-source ground station for global network satellites. It uses LoRa's Long-range, low-power features to transmit data from satellite to satellite and satellite to ground station. In their work [5] placed satellites at a fixed distance of 30 kms from the ground station, and their sensor data was transmitted through inter-satellite communication, and from inter-satellite comunication to the ground station through LoRa protocol.

B. Design of a Seven-Element Yagi Uda Antenna

In Rasaporlu [6], the team designed a Yagi antenna that was able to receive data from a TinyGS satellite. According to [6] the components used to achieve this communication are 5 elements Yagi-Uda Antenna they designed, ESP32 LoRa

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module, mini-Universal Serial Bus (USB) and Software Defined Radio (SDR). According to [6] the researchers simulated the Yagi-Uda on 4NEC2 software and obtained values gain of 8.67 dBi, reflection coefficient of 17.364 dB and the Standing Wave Ratio (SWR) of 1.31.

C. Adaptive Technique for LoRaCcommunication with Low Earth Orbit CubeSat

In the study conducted by Karunamurthy [7], they connected a smart energy meter to a power transformer to measure voltage, current and power. The measured values were then fed to LoRa IoT node using the serial Modbus protocol interface with the RS485 port of the smart. The values are converted into a packet and sent to the satellite, which in return send it back with the values to the ground station.

III. Methodology

Since the purpose of this paper is to anticipate the performance of a Low Power LoRa-WAN cubeSats in earth observation missions. Matrix Laboratory (MATLAB) simulations of two cubeSats orbiting the earth were performed based on computed LEO orbit parameters. The choice of two satellites is motivated by the need to minimize the possibility of missing on important information which can occur when a single satellite is used.

A. Simulation of CubeSat Orbiting

Fig. 1 shows the configuration of the inter-satellite simulation.

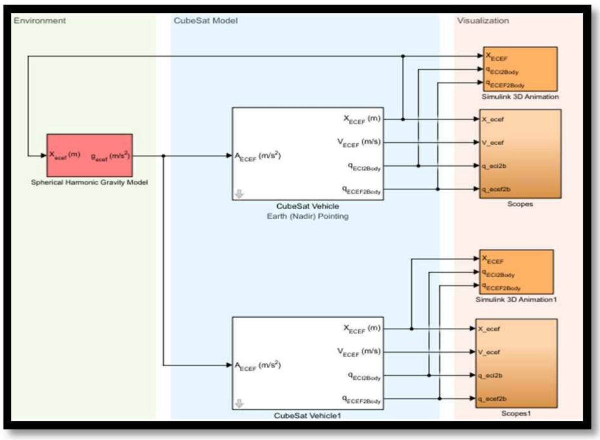

Fig. 1. Block diagram of the inter-satellite simulation in MATLAB.

CubeSat was simulated in MATLAB to gain insights, make informed decisions, reduce the risk, and have an overview of how the CubeSat will perform while orbiting the Earth. The block diagram in Fig. 1 shows two CubeSats orbiting the Earth. The red block is the spherical gravity model block. This block allows for the simulation of the space environment. The two blocks labeled “CubeSat vehicle” simulate the two CubeSats orbiting the Earth. The orange block enables visualization of the animation of the CubeSat in 3-Dimension.

The CubeSat will be equipped with an antenna, this antenna will need pointing mode to help it point towards the correct destination intended to transmit data, and the intended could the other satellite or ground station. The Pointing Mode will also help in adjusting the pointing position of the sensors to get the maximum accuracy in the data collection. Below is the block diagram of Point Mode Selection (Fig.2).

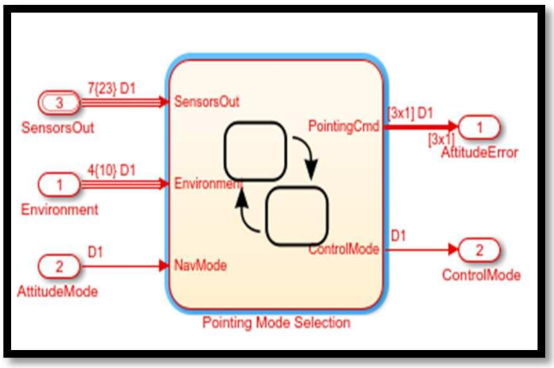

Fig. 2. Block diagram of the Point Mode Selection.

Attitude control ensures satellite operation, this involves using on-board computers, thrusters, and control algorithms to carefully manage the attitude of the CubeSat. Fig. 3 shows the block diagram of attitude control.

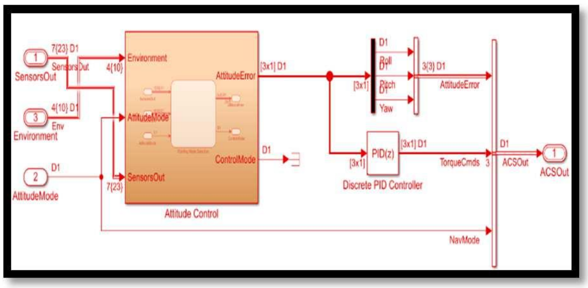

Fig. 3. Block diagram of Attitude Control

Fig.4 shows the block diagram of the attitude control system (ACS). The ACS is designed to perform the function of all the attitude determination such as calculating spacecraft attitude and its angular rates.

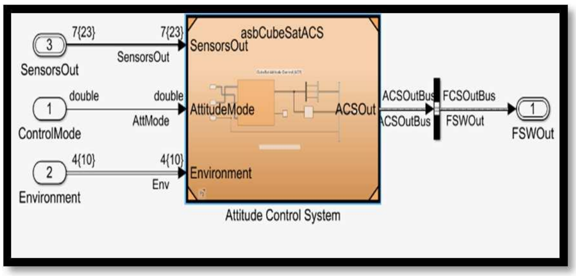

Fig. 4. Block diagram of the Attitude Control System (ACS)

Fig. 5 shows the block diagram of vehicle flight software for the CubeSat. This flight software is connected to the block diagram of control attitude. The forces and torque generated in attitude control are fed into the block diagram of vehicle dynamics, and the output of the vehicle dynamics is fed back into the vehicle flight software through the vehicle control sensors.

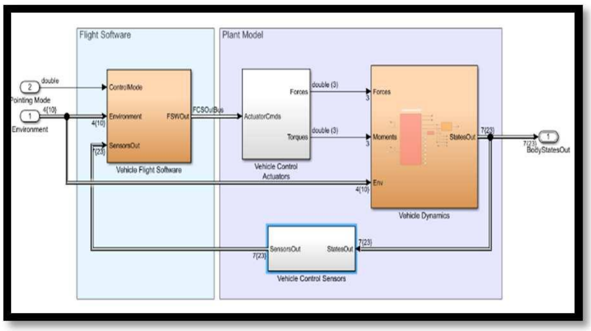

Fig. 5. Block diagram of the CubeSat flight software

B. Orbiting Parameters

To simulate the CubeSat in orbit, specific parameters must be determined to obtain accurate simulation data about the CubeSat. The following are the required parameters for the CubeSat orbiting in LEO.

Inclination angle: 97.30 degrees
Perigee: 480 km
Apogee: 508 km
Height of the CubeSat: 1700 km
Earth radius: 6 371 km

C. Parameters Governing Satellite Motion

Once in orbit, the satellite remains in that orbit, and obtaining a circular orbit if the linear velocity is calculated in a way that centrifugal forces caused by rotation around the earth are equal to earth's gravitation force when we ignore the atmospheric drag [8]. The velocity of the satellite is then calculated by the following equation [8] (Eq.1):

$$v = \sqrt{\frac{GM}{r}} \quad (1.)$$

$$v = \sqrt{\frac{(6.67 \times 10^{-11})(5.98 \times 10^{24})}{(1700) + (6371)}}$$

$$v = 222.305\ km/s$$

Where v is the satellite velocity, r the distance from the earth centre to the satellite, *GM* the earth gravitational forces.

The semi-major and the semi-minor of the satellite is calculated as the following. The value of these two is significant in describing CubeSat shape, attitude, orbital period and ground tracking [8] (Eqs.2 &3):

$$\alpha_{maj} = \frac{apogee+perigee}{2} \quad (2.)$$

$$\alpha_{maj} = \frac{508+480}{2}$$

$$\alpha_{maj} = 494 \text{ km}$$

$$\alpha_{min} = \sqrt{apogee \times perigee} \quad (3.)$$

$$\alpha_{min} = \sqrt{508 \times 480}$$

$$\alpha_{min} = 493.80$$

The eccentricity describes how elliptical the orbit is. An eccentricity of 0 means the orbit is circular, while an eccentricity of 1 means the orbit is parabolic. The mathematic representation of the eccentricity is given as [8] (Eq.4)

$$\varepsilon = \frac{r_a - r_p}{2\alpha_{maj}} \quad (4.)$$

$$\varepsilon = \frac{508-480}{2(494)}$$

$$\varepsilon = 0.028$$

The period that the CubeSat takes to complete the orbit is then calculated as the following [8](Eq.5):

$$T = \frac{2\pi r}{v} \quad (5.)$$

$$T = \frac{2\pi(1700+6371)}{(222.305)}$$

$$T = 228.11s$$

D. Kepler's First Law

Kepler's first law states that all planets move about the sun in an elliptical orbit, having the sun as one of the two foci of the ellipse [9] (Eq.6):

$$r = \frac{p}{1+\varepsilon cos\theta} \quad (6.)$$

Where **p** is the Semi-latus rectum, constant, **r** is the distance between the sun and earth at a given point of orbit, **ε** and is the eccentricity of the orbit, which the measure of how elliptical the orbit is, **θ** Is the angle between the radius vector and a reference direction.

The conservation of angular momentum is important for satellite stability, as it ensures that the satellite maintains a relatively constant orbital momentum throughout its orbit. According to Kepler's second law the satellite orbit period is shorter when satellite is at elliptical orbits, when they are closer to the earth and a longer orbital period happens when they are farther away, this is because he found out that the satellite covers equal areas in equal time intervals. According to Kepler second law the Sun-synchronous orbit, which are commonly used by earth observation satellite. The orbits are in a way that the satellite orbits plane processes around earth at the same rate as the earth revolves around the sun, resulting in satellite passing over the same earth position at the same time intervals during orbit, this also allow consistent lighting conditions for image and observation purposes. The mathematical presentation of the second law is as follows [9] (Eq. 7).

$$\frac{A}{T} = k \quad (7.)$$

Where **A** is the area swept out by the line connecting satellite and the earth, **T** is the time interval during which area is swept out, **k** is the constant value.

E. Kepler's Third Law

Kepler's third law state the square of orbital period of a planet is directly proportional to the cubes of its average distance from the sun [9]. In other words, the planets that are further away from the sun will take longer to complete one full orbit as compared to those planets that are closer to the sun (Eq.8).

$$\frac{p^2}{a^2} = k \quad (8.)$$

The expression of **a** is as per Eq. 9:

$$a^3 = \frac{\mu}{\omega^2} \quad (9.)$$

Where **P** is the orbital period of the planet and is the average distance between earth and sun (AU), **μ** is the earth gravitation constant (3.986005x1014 m^3/s^2), **ω** is the angular velocity of the satellite, **a** is the average distance of the satellite.

The angle formed between the moving satellites with reference to earth equator is known as inclination angle. The angle of inclination is given by [8] (Eq.10):

$$i = \lambda_{max} \quad (10.)$$

Maximum displacement due to λ_{max} (Eq.11)

$$D_{\lambda_{max}} = \alpha i \left(\frac{\pi}{180}\right)$$

$$D_{\lambda_{max}} = r \times \lambda_{max}$$

where $\lambda_{max} = i$

Alternatively, it is given by:

$$i = \sqrt{\psi \times 288} \quad (11.)$$

Maximum displacement due to ψ_{max}:

$$D_{\psi} = D_{\lambda}\left(\frac{\psi_{max}}{\lambda_{max}}\right)$$

$$D_{\psi_{max}} = r \times i$$

Where **ι** is the angle of inclination, **λ** is the maximum latitude deviation in degrees and **ψ** is the maximum longitude deviation from the ascending node.

The satellite location in space can be determined using the amount of elapsed time, the time elapsed can be found using [8] (Eq.12):

$$t = \left(\frac{T}{2\pi}\right)\left(u - \varepsilon sin(u)\right) \quad (12.)$$

Where **T** is the orbital period and **u** is the eccentricity anomaly of the current location of satellite.

The true anomaly of a satellite is the angle between the direction of periapsis (the point of closest approach to the central body) and the position of the satellite in its orbit, as measured from the center of the central body.

In other words, if you imagine a line connecting the center of the central body to the periapsis of the orbit, the true anomaly is the angle between that line and the line connecting the center of the central body to the satellite. This is given by the expression [8] (Eq.13):

$$v = cos^{-1}\frac{\varepsilon \times r}{|\varepsilon||r|} \quad (13.)$$

Where **v** is the orbital velocity vector, **ε** is eccentricity, **r** is the vector pointing towards ascending nodes

F. Azimuth and Elevation Angle

The angle formed by the intersection of the local horizontal plane, the plane formed by satellite, the earth station, and the earth centre with true north is known as the azimuth angle [8]. The azimuth angle can be calculated for the northern and southern hemisphere depending on where the earth station is located.

For the northern hemisphere, it is given by Eq.14:

$$A = 180 - A' \quad (14.)$$

(when earth station is towards west of satellite)

$$A = 180 + A'$$

(when earth station is towards east of satellite)

For the southern hemisphere, it is given by Eq.15 and 16:

$$A = A' \quad (15.)$$

(when earth station is towards west of satellite)

$$A = 360 - A'$$

(when earth station is towards east of satellite)

$$A' = tan^{-1}\left[\frac{tan|\theta_s - \theta_L|}{\theta_l}\right] \quad (16.)$$

Where: θ_s is the satellite longitude, θ_L is the earth satellite longitude, θ_l is the earth station latitude.
The coverage is expressed as per the following Eq.17 while the centrifugal forces F_c are represented as per Eq.18**:**

$$2\alpha = 2sin^{-1}\frac{R_e}{R_e + H}\cos(E) \quad (17.)$$

$$F_c = \frac{mV^2}{R_e + H} \quad (18.)$$

Where R_e is the earth radius, **H** is the altitude, **V** is the velocity and **m** is the mass.

Fig. 6 shows the CubeSat and its required parameters as calculated by the preceding equations. These parameters are edited to obtain accuracy and a realistic 3D animation of the CubeSat in MATLAB.

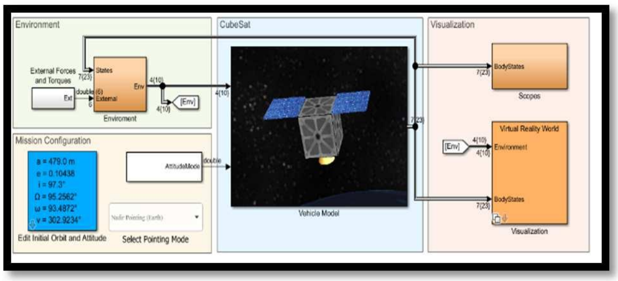

Fig. 6. Block diagram of the CubeSat with Parameters

Fig. 7 shows the 3D animation obtained from MATLAB simulation of the CubeSat orbiting Earth at a velocity of 222.305 km/s taking 228.11 seconds, with semi-major of 494 km and semi-minor of 493.80 km.

Fig. 7. CubeSats Orbiting.

The red dot is the representation of the ground station while the green line represents signal transmitted between the ground station and the other CubeSat. After simulating the cubeSat on orbit came the communication part including an antenna in the picture.

G. Simulation of a ¼ Wave Antenna

The monopole quarter wavelength was simulated using MMNA GAL software, Fig 8 shows the structure of the monopole antenna. It has a gain of 6.04 dBi, and standing wave ratio (SWR) of 1.57.

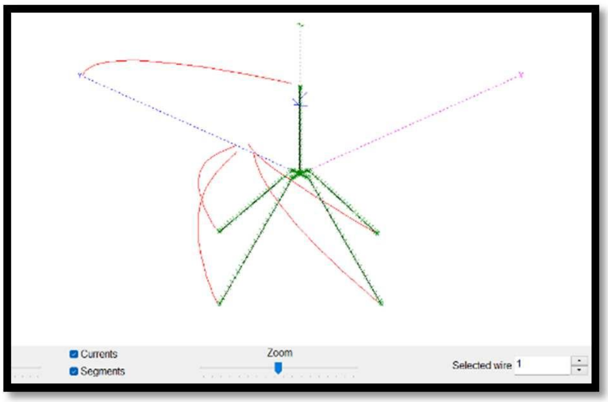

Fig. 8. ¼ wavelength 433 MHz Monopole antenna

IV. RESULTS

The results obtained from the simulation are shown in Table 1. The results indicate that the communication frequency is 433 MHz, the transmission line impedance is (78-j0.152) Ω i.e. minimal line reactance, the SWR is 1.57 i.e. the maximum voltage is 1.57 higher than the minimum voltage level at half wavelength and the gain is 6.04. The same results are a match of the results simulated in MATLAB as it can be seen in Fig.6 in the blue box.

Overall, the results promise satisfactory communication performance between the satellite and the antenna.

TABLE I. DATA OBTAINED FOR 433MHZ MONOPOLE ANTENNA SIMULATION

F (MHz)	R (ohm)	jX (ohm)	SWR 50	Gain	F/B	ELE
433	78.54	-0.152	1.57	6.04	-0.02	3.0

Fig. 8 shows a 2-dimensional far-field plot of the antenna and it corroborates the results displayed in Fig.6.

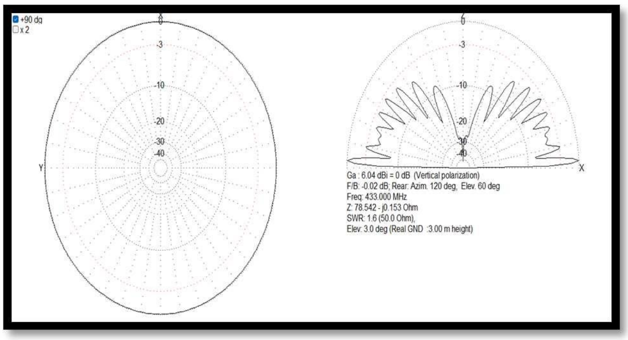

Fig.8. 2D Far Field Plots

Furthermore, Fig. 9 shows a 3D view for a far field obtained from simulating the 433MHz monopole antenna.

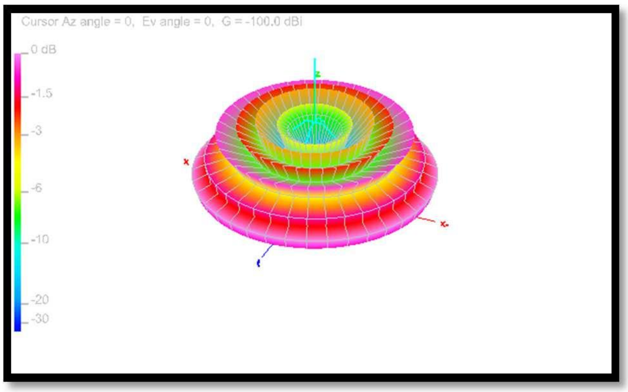

Fig. 9. 3D Far Field Plots

V. CONCLUSION

LoRa LPWAN CubeSats hold the potential to make space exploration seamless and affordable as well as improving communication quality regarding earth observing missions. From the simulation results, CubeSats are expected communicate effectively with the antenna. When it comes to earth observation and remote sensing, LoRa LPWAN

CubeSats are deemed more efficient in detecting water underground by sensing the surface temperature and measuring the difference in gravity using the gravitational gradiometer and transmitting the information to IoT devices. Future work envisages the inclusion of the CubeSat thermal power in the study.

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