Deployable Fresnel Zone Plate antenna for CubeSats

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Abstract

Earth Observation satellite missions can provide global and frequent coverage. In the past decade we have seen an explosion of these missions based on three unit CubeSats, notably with Planet and Spire constellations of visible and near-infrared imagers and GNSS-Radio Occultations payloads. One of the most important parts of these type of payloads is the antenna, which is limited due to the dimensions of the CubeSats. Today, the largest deployable antenna for CubeSats has a diameter of 50 cm and it was part of RainCube rain radar. ESA is currently sponsoring two studies to develop a 1 m deployable reflector antenna for CubeSats. Although the most common solutions are the deployable reflectors, Fresnel Zone Plate antennas are a simple type of antennas that can overcome some of the technical limitations of these reflectors.

In this paper we will present the design and tests of a deployable Fresnel Zone Plate antenna with 155 cm diameter, at a distance of 58 cm from the feeder. During the design, the modularity of the system has been considered, so that other antenna types can also be deployed. This antenna has a triangular shape, and each end is attached to a telescopic carbon fiber rod, which is deployed by means of a toothed belt that pushes them from its inner part. Each toothed belt is pushed with a DC motor.

If accepted for a launch of opportunity, this antenna will be used in a GNSS-Radio Occultations payload onboard 3Cat-8, one of the future satellite missions of the UPC NanoSat Lab.

Keywords

Fresnel Zone Plate, Deployable antenna, CubeSat

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Acronyms/Abbreviations

GNSS	*Global Navigation Satellite System*
U	*Unit*
FZP	*Fresnel Zone Plate*
PCB	*Printed Circuit Board*

1. Introduction

During the last years, Earth Observation satellite missions have gained a lot of interest basically using three different techniques. Some use hyperspectral cameras, other satellites use Microwave Radiometry or Global Navigation Satellite System (GNSS) - Reflectometry and other spacecrafts use radars. Although, these satellites have considerable dimensions, the current trend in this industry is the miniaturization of the payloads and the whole spacecraft as much as possible.

The appearance of the CubeSat [1] form factor standardized the satellites envelope and weight, and has played an important role in the miniaturization process. These satellites are described by Units (U), so a 1U satellite is 10 cm x 10 cm x 10 cm, with a weight of no more than 2 kg. Depending on the number of units that are used, there are different types of CubeSats. With CubeSats, opportunities of faster and more cost-effective development and launch have appeared.

One of the main requirements of these payloads is to have a high spatial resolution, since the resolution is too low, the area covered is large, and the small features cannot be identified. In the case of radio frequency payloads, this spatial resolution is directly related to the directivity of the antenna in the following way: the higher the directivity, the smaller the beamwidth, and the better the resolution. The antenna directivity is proportional to the effective area, and this one is proportional to the antenna dimensions. For example, for a reflector antenna, the directivity increases with the square of the radius of the reflector, or for a Yagi antenna it increases with the number of passive elements. Thus, there is a trade-off between the directivity of the antenna (i.e. having a large antenna) and space available inside a CubeSat, making it difficult to allocate them.

This work is focused on the development of a deployable Fresnel Zone Plate (FZP) antenna for GNSS radio occultations that will be carried in the 3Cat-8 mission, a 6U CubeSat under development by the NanoSat Lab in collaboration with some other research groups. The idea is to have the antenna completely stowed inside the CubeSat during the launch in order to take profit of the standardized deployers for this type of satellites and once the satellite has been put in orbit the antenna must be deployed achieving big enough dimensions to increase the performance of the subsystem in comparison of what has been used until now. This work pretends to cover both the electromagnetic design of the antenna and also the deploying mechanism which is intended to have a certain level of modularity in order to be adapted for different types of antennas or even other type of payloads.

2. Antenna – Electrical design

It is known that, from the Huygens principle [2], any point of a wavefront, can be considered as a source of new waves that expand from that point. Having said that, Fresnel Zones theory says that, having two antennas, positioned in two points, A and B, and working one of them as transmitter and the other one as receiver, the transmitted waves can travel directly from A to B in a straight line, or can arrive the receptor following other paths by reflection, that means, a longer path that introduces a phase different between the direct and reflected beams which, in some cases is destructive, giving place to the destruction of the waves. Nevertheless, the reflection can also cause that the waves arrive in phase at the receiver, enhancing the received wave.

Fresnel zone plates antennas are a type of flat antennas based on the Fresnel zones principle, and they achieve the focusing effect by controlling the phase shifting property of the surface using diffraction instead of refraction or reflection.

This plate consists of a set of concentric rings, known as Fresnel zones, which alternate between being opaque and transparent. Signal hitting the zone plate will diffract around the opaque zones. The zones can be spaced so that the diffracted signal constructively interferes at the desired focus since all radiation from each zone arrives at the focal point in phase within $\pm\pi/2$ range, concentrating the power in the focal point.

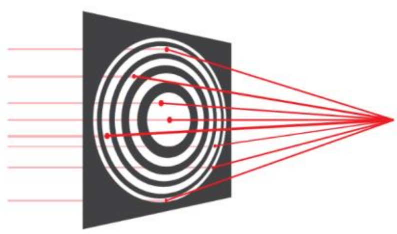

Figure 1. Fresnel Zone Plate [3]

The radius of every zone is defined according to Eq 1, where F_1 and F_2 are the two focal lengths, λ is the wavelength at the operational frequency and n is the number of the ring.

$$r(n) = \sqrt{\frac{n\lambda F_1 F_2}{F_1 + F_2}} \qquad (1)$$

Knowing that most of the CubeSats are orbiting at LEO orbits, the first focal length (F_1) has been set to 500 km and departing from Eq 1 the rest of parameter values have been found trying to optimize the directivity of the antenna. To do the simulations, an electromagnetic analysis software called CST has been used, and basically with a simplified version of the antenna that had a patch antenna matched at 1575.42 MHz as a feeder, and metallic rings at a distance F_2.

The optimum configuration of the antenna is with a focal length of 580 mm, and with four zones with the radius that can be seen in Table 1 and obtained from Eq 1.

Table 1. Radius of the FZP rings

Zone	1st	2nd	3rd	4th
Radius (mm)	345.7	507.1	642.6	766.1

The obtained radiation pattern for a given plane can be seen in Figure 2 which will be the same for any other plane due to the symmetry of the antenna. It achieves a directivity of 18 dBi and a beamwidth of 8.2º.

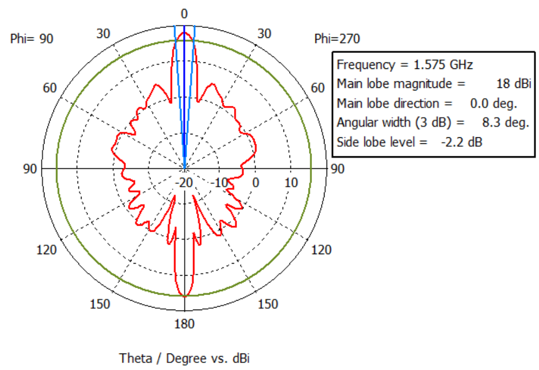

Figure 2. FZP radiation pattern

The real prototype from Figure 3 was designed with three carbon masts that were holding a single ring made with metallic tape. The design was done at 2.7 GHz with the intention of reducing the dimensions of the antenna and measure it in the anechoic chamber.

Figure 3. FZP prototype with two zones

3. Deploying mechanism

As commented in the introduction, the antenna must be stowed during the launch so a deploying system needs to be designed.

Having in mind the triangular shape of the FZP antenna, the idea is to have its three corners attached each one to a mast that will hold it in a flat shape, similar to the one designed for the measurements in the anechoic chamber. Since the FZP is considerably large, the three masts will need to have some deploying mechanism in order to reach the desired deployed length. In Figure 4 it can be seen a simple concept design with which this system can be understood in a better way and all the parts can be identified.

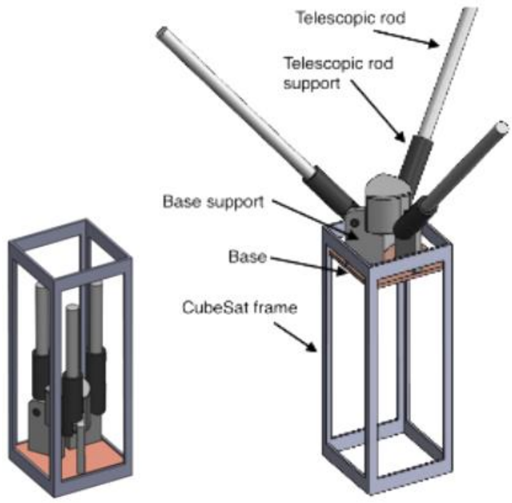

Figure 4. Deploying mechanism concept

In the left draw of Figure 4, it can be seen the stowed configuration with all the system completely inside the CubeSat structure. For the deployment, since the three masts need to rotate some degrees in order to achieve the triangular shape, the system needs to be lifted up from inside the CubeSat until it reaches the top surface of the spacecraft, as it could be seen in the right figure.

3.1. Lifting mechanism

The implemented idea is based in how the CubeSat deployers work. The system should be pushed by a spring that is compressed under the base during the launch storing an elastic potential energy and when it is time to deploy, a mechanism should unblock it and the potential energy becomes kinetic energy which should be enough to lift up the base and all the deployment system until they reach the final position.

The final implementation, uses four springs located in the corners of the satellite structure. These 300 mm long and 12 mm diameter springs have inside an inner 6 mm diameter aluminum circular guide that is part of the satellite frame. Since these guides go from the low part to the top of the satellite structure, they give the frame a lot of rigidity, giving the possibility of considerably simplifying the side walls of the structure and thus freeing up space for the entire deployment mechanism. These guides are also used for the base guiding, which has four linear bearings through which the guides pass, and they make sure that the base doesn't move in the lateral directions.

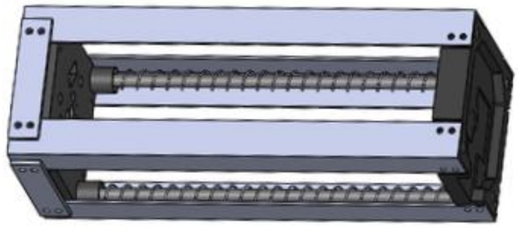

Figure 5. 3U CubeSat prototype frame with the lifting up system

3.1.1. Locking mechanism

Once the system has been lifted up to its final position, it must remain there fixed without no more vertical movement. To do so, three neodymium magnets are attached to the base and three more to the top part of the satellite frame ensuring that once the base has reached its final position, the attraction between the pairs of magnets make to the base not possible to return back and it stays fixed to the top part of the frame.

3.1.2. Holding mechanism during the launch

During the rocket launch, the system must remain stowed and the spring must be compressed. These springs have a considerable elastic potential energy and a robust system must ensure that it will not unlock the system, and cause any damage.

The used system is an adaptation of the one used in the NADS subsystem of the ^{3}Cat-4 mission [4], taking into account the differences between the two satellites. The implemented system is based in three Dyneema lines that are attached to the base of the deploying mechanism and also to the base of the satellite structure. This type of Dyneema wire has a diameter of 0.25 mm and can hold weights up to 23.5 kg, having enough strength to hold all the springs compressed. In the lower part of the satellite structure there is a Printed Circuit Board (PCB) with a burning system based in Kanthal wires. Kanthal is a family of iron-chromium-aluminum alloys with a special ability to withstand high temperatures and having intermediate electric resistance.

In this implementation, the Dyneema wires pass through this Kanthal wires and once it is a applied a 3.3 voltage to these Kanthal wires, the high amount of current makes the temperature of the wires increase with the result of cutting the Dyneema lines and allowing the system to be unlocked and lifted up.

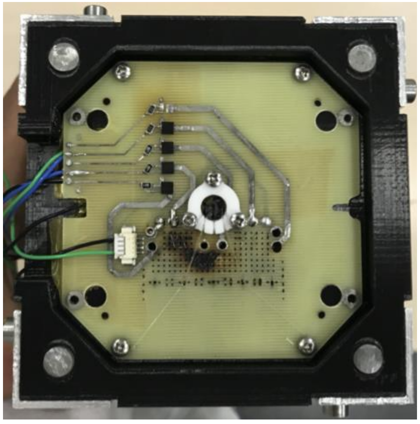

Figure 6. PCB for the Dyneema lines burning

3.2. Masts deployment

Once the deploying system has been pushed by the springs and has reached its final position in the satellite structure, it's time for the deployment of the FZP.

The three masts that hold the FZP are three telescopic carbon fiber rods composed of cylinders of different diameter. These cylinders have a folded length of 17 cm and a deployed length of 200 cm. The system is the same used as for the fishing rods.

3.2.1. Angular movement

Once the system has been lifted up, these rods need to rotate some degrees until they reach the appropriate angle. This rotational movement is ensured by means of a rotational spring located near the center of rotation of the rods as it can be seen in Figure 7.

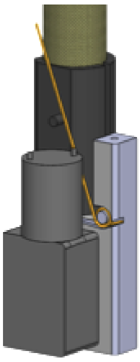

Figure 7. Rotational spring for the angular movement of the rods

Once these rods have reached their final position, they need to stay fixed without having any rotation. The forward movement is avoided in the final part of the deployment when the FZP starts making strength and avoids this movement. The backwards movement is avoided with a breaking system that has been designed minimizing as much as possible the occupied space. As it could be seen in Figure 8, the axis of rotation of the carbon rod supports, has a flange that is maintaining the break folded. Once the rod has rotated and the flange has also rotated, a small spring pushes the brake to its final position and this one fits with the flange shape avoiding the backwards movement.

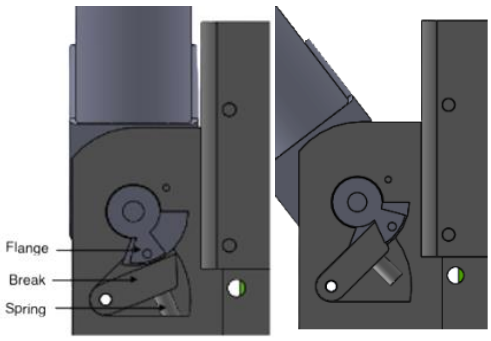

Figure 8. Angular movement brake

3.2.2. Telescopic deployment

The final part of the deployment is basically to deploy the telescopic rods until they reach their final length. To do so, there is a toothed belt that goes inside the rods and pushes them from its inner part. At the same time these toothed belts need to be pushed with a motor. The idea of using only one central DC motor was considered but then it was substituted by the idea of using three of them one per each rod. The use of three motors has several advantages like being able to deploy the three branches sequentially reducing the peak power consumption, it simplifies the gear system that is needed for the case of using a single motor and also increases the modularity of the system since each mast can be operated independently and have different deployed lengths. Each motor is attached to the pieces that hold the rods called base supports, and its axis of rotation is attached to a gear that pushes the toothed belts. This configuration can be properly understood in Figure 9.

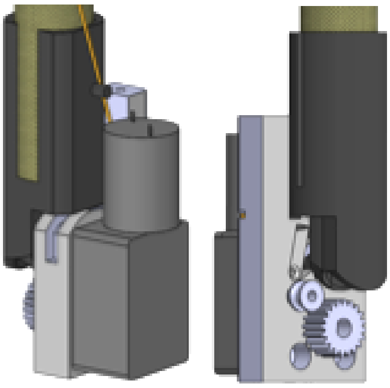

Figure 9. DC motors attachment

The three toothed belts are stored in the bottom part of the base and each one is rolled in a reel that has an inner hole with a strategic shape to guide the belt to the position of the gear where the motor pushes it.

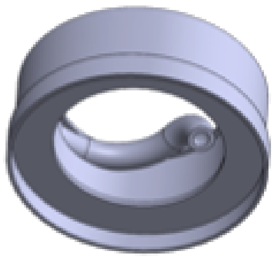

Figure 10. Toothed belt reel

4. Results and discussion

4.1. ·Electromagnetic analysis

After the measurements in the anechoic chamber of the prototype, the directivity results were compared with the ones obtained in the simulation. The measured one was 12.5 dBi and the one from the simulation was 14.8 dBi. There are 2.3 dB of difference which is a considerable amount taking into account the logarithmic scale. There are several factors that could have affected but the most important ones are the manufacturing imperfections, the non-perfect conductivity of the materials and the movement of the support of the anechoic chamber that caused some vibrations on the FZP among others.

4.2. Deployment

All the designed pieces for the deployment system have been 3D printed in order to make some testing on the deployment before start manufacturing with aluminum and all the space rated components that are needed like the motors, the PCB or the bearings. In Figure 11 there can be seen three pictures of the prototype system in the three stages of the deployment. The used FZP is a cloth without the conductor rings that has been used to simulate the tension that a similar and definitive one must be doing once the antenna is completely deployed.

Figure 12. Complete system prototype

As a first prototype the system performed well both for the lift up system and for the telescopic deployment of the rods.

5. Conclusions

Regarding the electromagnetic simulations, one of the points that needs to be improved is the Front to back ratio. As it could be seen in radiation pattern, the principal lobe has nearly the same radiation levels as the back one. One of the possible solutions that is being considered is to implement the conductor rings with a conductor material in the top part and an absorbent material in its bottom part to avoid the signals coming from the back part of the satellite to be also detected by the feeder.

Regarding the deploying system, a general conclusion would be that the prototype is performing well and achieving the expected goals but there is a lot of work to do until it is ready to be launched in a space mission. There are a lot of innovative ideas inside each part to cope with all the requirements and these ideas now need to be exhaustively tested under space conditions with a thermal vacuum chamber and a shake table to validate them.

One important aspect is that although the system seems to be really specific for this application, it has a lot of modularity. For example, in case that it is needed to deploy a specific sensor some distance away from the satellite, using a single rod and adapting the rest of the parts it could be done really easy. Another example could be the case of deploying a reflector with a certain offset respect to the satellite axis, it could be done by varying the length of the three branches and also modifying the angle of rotation of these branches.

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References

[1] CubeSat standard. https://www.cubesat.org, last visited: 1st March 2022.

[2] Huygens' Principle. Huygens–Fresnel principle - Wikipedia, last visited: 1st March 2022.

[3] Berkley Lab. Fresne zone plate behaviour. default (lbl.gov), last visited: 1st March 2022.

[4] N a n o S a t L a b . 3 c a t - 4. ³Cat-4 — NanoSat Lab — UPC. Universitat Politècnica de Catalunya, last visited: 16th March 2022.