Development of antennas for the cubesat NANOSTAR project (Moon Flyby)

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***Abstract*—The standardized shape, size, and weight of Cubesats allows for low costs in production, transporting, launching, and deploying into space. A 6U Cubesat is chosen to complete a moon flyby mission in the NANOSTAR project. The main objective for the mission is to retrieve science data in the form of lunar surface photographs.**

This thesis focuses on a secondary mission, that will involve mapping of the moon surface using radar-based altimeter studies. The thesis addresses the design of low-cost metal-only reflect-array antenna, operating in the K_u band, that can be flown with the 6U cubesat The use of metal makes the design of the antenna compatible with other Earth orbit missions.

A reflect-array of slot-type unit cells with stubs that were adapted from an existing model and modifications to the unit cell design were made in order to achieve a full 360° range. Using this cell and creating a reflect-array with dimensions of $216{*}168mm^2$, measured results show a maximum gain of $24.5\ dB$ at $14\ GHz$.

To improve the realized gain of the reflect-array and to study if the sharp phase transitions affected the reflect-array performance a so-called phoenix-type cell solution is presented and a gain of $25.34\ dB$ was obtained.

Even though an improvement was made with the phoenix cells, due to high costs in the manufacturing process, the slot-type cells were chosen for the secondary mission since the cost of production would be many times cheaper.

***Index Terms*—CubeSat, NANOSTAR project, Metal-only Reflect-array, Slot-Type Unit Cell, Phoenix Unit Cells, K_u Band, Altimetry, Radar**

I. Introduction

Thousands of different types of satellites are available nowadays ranging from $1000\ kg$ weight to $0.1\ kg$. Cubesats are small satellites that have gained a high popularity in the last years due to their very specific standards that allow reduce costs and the mass-production of components

Student teams from all universities compete to create the best preliminary design of a Moon-flyby Cubesat mission according to a given set of requirements. The mission to be carried out by the designed Cubesat consists on doing, at least, one flyby to the Moon. A flyby can be defined has a flight past a point, especially the close approach of a spacecraft to a planet or moon for observation. During the flyby, the spacecraft does not orbit the moon, instead the moon is used for gravity assist.

For this mission a planar antenna of the type reflect-array or transmit-array that can be installed in the micro-satellite is going to be designed. The antenna will have to be foldable in order to be compatible with the launching phase. Possible missions during the flyby will be the communication between the Cubesat and Earth, and the mapping of the moon surface using radar techniques that will allow an altimetry study.

To accomplish this objectives it is intended to project, fabric and test a lab version of a reflect-array planar antenna. The antenna is based on a reflect-array configuration to minimize occupied volume while in the undeployed stage. It is designed to operate in the K_u band, and it is compatible with linear or circular polarization. This antenna will use all-metal unit cells, to make the design compatible also with other Earth orbit missions, where dielectric based antennas might be susceptible to electrostatic charge buildup and arcing.

II. Formulation and Methods

A. NANOSTAR Mission Limitations

To design a working reflect-array capable of completing the NANOSTAR Moon Flyby mission with the objective of studying the moon surface, a better understanding of this mission and its limitations is needed.

The main objective for the creation of the reflect-array antenna, is to provide a linear polarized, high gain antenna solution for the K_u band (12-18 GHz), that can be integrated into a 6U Cubesat [1], that can be seen in figure 1, for an altimetry study of the moon surface in a flyby mission, meaning that the Cubesat will at one point be so close to the moon that its possible to gather scientific data. For this mission, the periselenium pass shall not be higher than 100 km from the moon's surface.

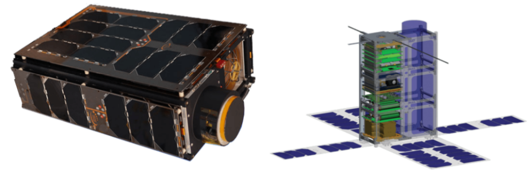


Fig. 1. 6U Cubesat [2]

The Cubesat will have a dimension of 120x240x360 mm^3 [3] and so the dimension of the reflect-array antenna shall not exceed 240x360 mm to guarantee that the reflect-array antenna doesn't need to be split and folded in different parts in order to fit in the Cubesat as a single piece .

For this thesis a 18 by 14 unit cells with a total dimension of 216x168 mm^2 reflect-array antenna is chosen so that it can be fit in the Cubesat satellite without any extra problems.

Another important factor to take into account is the limitation regarding the antenna power supply. For this specific mission at least 1 W of power is reserved for the antenna, to satisfy the requirements of the mission. In [1] some preliminary studies were made regarding the maximum limit of power to the antenna that the Cubesat could make. Assuming that during communications, science and eclipse mode, the thruster is switched off, a maximum power of 10 W for the antenna is permitted in order to facilitate the functioning of the thruster after the eclipse time.

B. radar Range Equation

Standard form of radar range equation of the target is the maximum range that the antenna can be from the target which means that the echo signal must equal a minimum detectable received signal.

To determine the power of the received signal, it is necessary to understand that power density (S_{di}) is the ratio of power and area. For an antenna that radiates equally in all directions (isotropic):

$$S_{di} = \frac{P_t}{4\pi R^2} \tag{1}$$

Where:

- S_{di} Power density
- P_t is the transmitted power by the radar
- R distance of the radar to the target

As a general rule, radars use directional antennas. Therefore, the power density, S_{dd} for a directional antenna will be:

$$S_{dd} = \frac{P_t G}{4\pi R^2} \tag{2}$$

Where:

- G is the Gain introduced by the directional antenna.

After the power is transmitted to the target, it will collide with it and be radiated in different directions. The amount of power that is reflected back towards the radar is dependent on the Cross Section of the target's material. The radar Cross Section (RCS), σ , is the measure of the ratio of backscatter density in the direction of the radio receiver, which means the measure of the target ability to reflect radar signals in the direction of the receiver. For the moon surface, a RCS presented in [4] was taken into account.

The power density S_{de} of the echo signal at the radar is represented as follows

$$S_{de} = S_{dd} \frac{\sigma}{4\pi R^2} \tag{3}$$

Substituting the equation 2 in the equation 3

$$S_{de} = \frac{P_t G}{4\pi R^2} \frac{\sigma}{4\pi R^2} \Rightarrow S_{de} = \frac{P_t G \sigma}{(4\pi)^2 R^4} \tag{4}$$

The amount of power received in the antenna, P_r, also depends on the effective aperture,A_e, of the receiving antenna.

$$P_r = S_{de} A_e \tag{5}$$

The effective aperture can be mathematically defined has

$$A_e = \frac{G\lambda^2}{4\pi} \tag{6}$$

Substituting equation 6 and equation 4 in equation 5

$$P_r = \frac{P_t G \sigma}{(4\pi)^2 R^4} \frac{G\lambda^2}{4\pi} \Rightarrow R = \left[\frac{P_t G^2 \sigma \lambda^2}{(4\pi)^3 P_r} \right]^{1/4} \tag{7}$$

One of the main factors which determines the maximum range performance of the radar is the minimum received power P_{min} and all receivers are designed for a certain sensitivity level. The maximum range of the radar R_{max} is obtained by defining a minimum sensitivity, S_{min}, needed for the connection. For radar applications, a sensitivity of -100 dBm is typically taken into consideration [5].

$$R_{max} = \left[\frac{P_t G^2 \sigma \lambda^2}{(4\pi)^3 S_{min}} \right]^{1/4} \tag{8}$$

Where σ is an approximated value studied in [4] for lunar radar observations of the moon surface:

$$\sigma = 0.33\pi S_r^2 \tag{9}$$

- S_r satellite footprint radius

C. Desired Phase on each Unit Cell

Reflect-arrays have a basic operating principle similar to that of the planar antenna arrays. In a planar antenna array, a uniform phase distribution on the aperture will result in a collimated beam that is normal to the plane of the array. In order to focus the beam in a desired direction, a phase distribution is assigned to the unit cells. In the case of reflect-array one needs to also take into account the feed antenna position.

The feed antenna will have a fixed position at a distance, d_i, of the reflect-array. The apparent source of radiation in the feed is designated as the phase center of the antenna. The feed will originate a spherical wave from the phase center. It is considered that the reflect-array unit cells are in the far field of the feed antenna; the incident electromagnetic field on each unit cell is a spherical wave that excites the element with a certain incident angle, that varies depending on the position of the element relatively to the feed antenna.

The electromagnetic field generated by the feed on the reflect-array has a phase that is proportional to the distance d_i of the feed designated spatial phase delay. To achieve a collimated beam, each of the unit cells needs to compensate the phase difference from the center of the array to the i^{th} unit cell. Figure 2 shows a generic model for a reflect-array and respective feed.

As mention before, the reflection phase of the unit cells need to compensate for the special phase delay, *spd*, that goes from the feed center to each unit cell. This is mathematically expressed in equation 10

$$\phi_{spd} = -k_0[d_i - d_0] \tag{10}$$

Where:

- k_0 is the wave number in free space for the central frequency

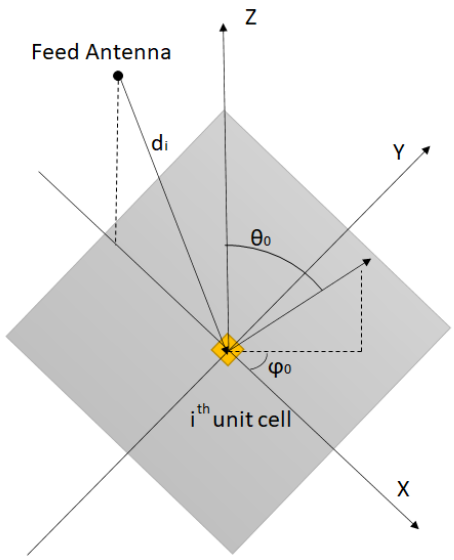


Fig. 2. Reflect array antenna diagram

- d_i distance between the i^{th} unit cell and the feed phase center
- d_0 distance to the center of the reflect-array

This phase distribution will create a collimated beam in the direction of Z. To control the collimated beam in any direction, a progressive phase must be added. Using the Cartesian coordinate system of figure 2 the position of each unit cell corresponds to a certain x_i, y_i, with i representing the i^{th} unit cell, and a beam direction (θ_0 , Φ_0) , it is possible to mathematically express the progressive phase needed to control the direction of the collimated beam, equation 11.

$$\phi_{pp} = -k_0(x_i \sin\theta_0 \cos\varphi_0 - y_i \sin\theta_0 \sin\varphi_0) \tag{11}$$

Using equations 10 and 11 it is possible to determine the required phase distribution, to create a collimated beam, for each of the unit cells that form the reflect-array.

$$\phi_{pp} = \phi_{spd} + \phi_{UnitCell} \tag{12}$$

$$\phi_{UnitCell} = k_0\left(d_i - d_0 - \sin\theta_0(x_i \cos\varphi_0 + y_i \sin\varphi_0)\right) \tag{13}$$

D. Reflect-array Aperture Dimension

To determine the planar aperture diameter D_A an approximation of the Franz's formulas is used, taking into account the intended directivity of the antenna [6].

$$D_{max} = \eta(\frac{4\pi\sigma}{\lambda})^2 \tanh{(\frac{D_A}{4\sigma})^2} \cos\alpha_0 \tag{14}$$

With

$$\sigma^2 = \frac{D_A^2}{8\tau \ln 10} \tag{15}$$

Where:

- α_0 Outgoing angle
- η Aperture efficiency
- λ Wavelength

Plugging equation 15 in equation 14, the planar aperture with diameter D_A is obtained

$$\frac{D_A}{\lambda} = \frac{1}{4\pi}\sqrt{\frac{8\tau \ln 10 D_{max}}{\tanh\frac{\tau}{2\ln 10}\cos\alpha_0\eta}} \tag{16}$$

E. Preliminary Reflect-array Design

Having defined the aperture dimension of the reflect-array antenna, using equation 14 it is possible to determine the maximum theoretical directivity, zero losses, that the reflect-array will have.

Considering:

- $\eta = 1$
- $D_A = 216mm$
- $\tau = 0.5$
- $\alpha_0 = 45°$

Using the equation 14 the maximum theoretical directivity of 28 dB is obtained.

It is considered that the feed is at a height, F, of 132 mm, positioned at 132 mm of the center of the reflect-array antenna $[A]$. Figure 3 represents a simple assembly possibility for the reflect-array antenna and feed horn antenna in the Cubesat.

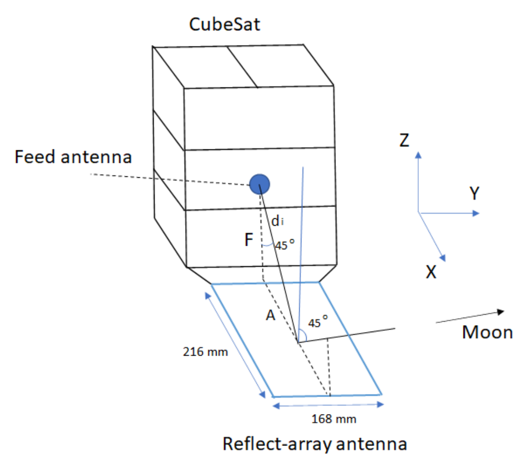


Fig. 3. Reflect-array antenna and feed horn antenna, integrated into a Cubesat structure

Considering the feed in the previous mentioned positions, with an input and output beam of 45°, the necessary phase distribution for each unit cell can be calculated with equation 13 and is represented in figure 4

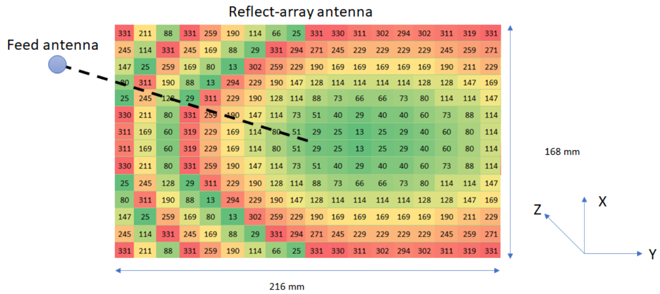


Fig. 4. Necessary phase shift to achieve beam collimation for a feed placed in the left side of the reflect-array. Each pixel represents one 12 x 12 mm^2 unit cell with the respective phase indicated in degrees

III. Metal-only unit cells design

The first step in the creation of the reflect-array antenna is the characterization of the phasing elements. An in-depth analysis must be made to better understand the phase-shift produced on the reflected field of each unit cell. A novel planar metal-only reflect-array antenna using slot-type elements was introduced in paper [7]. This unit cell uses a unique unified slot structure to prove that the commonly used dielectric substrate applied in conventional reflect-array antennas can be removed, leading to a metal-only reflect-array. The design of the unit cell consists of two properly separated stainless sheets with an air gap in between, dimensioned for 12.5 GHz. Figure 5 shows the unit cell design.

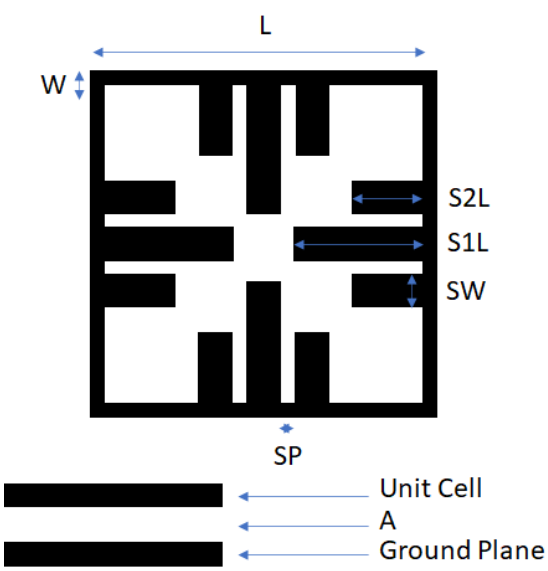


Fig. 5. Metal-only slot-type element

The reflection phase of the slot-type element changes accordingly to the central stub length that is variable. In paper [7] a phase range of 254° was obtained. Even though this range is acceptable in practice, improvements can be made for a wider phase shift range.

For radar applications, the best frequency band for altimetry studies is the K_u band. For the purpose of this thesis, the frequency of 14 GHz is chosen because it is in the middle of the K_u band, leading to the need of only one horn antenna during the experimental phase. Taking into account that the prototype is made out of a sheet of copper, the copper thickness of 0.5 mm was taken in to account for the rest of the simulations. Firstly the unit cell, in figure 5, dimensions are adapted for the 14 GHz frequency and then simulated using CST-MWS. Table I shows the chosen dimensions for the unit cell. After simulations the following phase response s_{11} in figure 6 was obtained for three different feed incident angles.

TABLE I
Slot-type unit cell adjusted parameters for 14 GHz

Parameters	Value[mm]
L	12
S1L	0-5.2
S2L	3
SW	0.8
SP	0.5
W	0.4
A	1.5

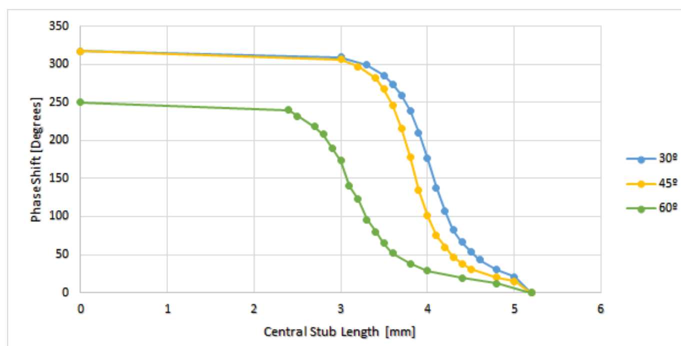


Fig. 6. Simulated phase responses S_{11} of the slot-type element for an incident angle of 30°,45° and 60° at 14 GHz

With the new modified parameters the unit cell shows a phase range of 317°, that is an improvement when compared to the measured results obtain in the paper [7]. The incident angle of 45° for the feed antenna is chosen to simplify the assembly of the reflect-array antenna and feed horn antenna in the Cubesat. It's also important to analyse the s_{11} amplitude response that is represented in figure 7. The s_{11} amplitude response represents how much power is reflected from the antenna, and therefore is known as the reflection coefficient, for this case we want an $|s_{11}|$ as close to 0 dB as possible, meaning that all the power is reflected from the reflect-array. For the 45° incident angle a remarkable reflection coefficient is obtained ranging from $0.05 - 0.35$ dB within the band of interest.

It is well known that reflect-arrays have a disadvantage when it comes to bandwidth since it is limited due to the

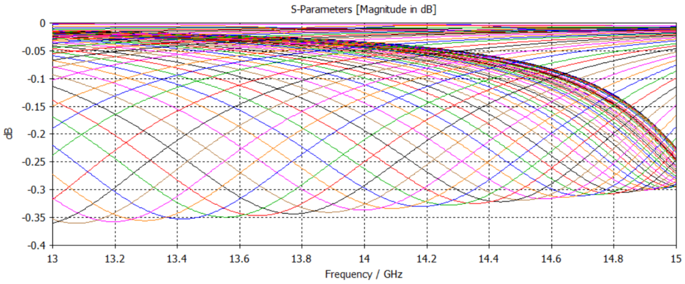


Fig. 7. S11 magnitude of the designed unit cell. Each color represents a different S1L length.

dispersive nature of resonant planar elements. One other problem with reflect-arrays is the fact that coupling effects, which represents the electromagnetic interaction between the antenna elements in an array, are difficult to take in to account for since all unit cells in the array are different from each other. These differences are most noticeable in sharp phase transitions, meaning that when the unit cell is required to jump a complete 360° cycle, may lead to severe degradation in the array pattern.

To resolve this problem and try to obtain better results than in the previous unit cell using slot-type elements with stubs, a novel planar metal-only phoenix cell is presented in [8], the design consists of double-square loops, a square patch, and a connecting stub that unites them into a whole piece

Some modifications on the phoenix cell design were made. The original unit cell consisted of two separated stainless sheets without any dielectric substrate in between, walls were created to join these two sheets making the unit cell a single solid piece and removing the need for the connecting stub. Since the unit cell was dimensioned for 12.5 GHz, its dimensions were once again modified to fit the wished 14 GHz frequency. The new phoenix cell can be seen in figure 8 and respective dimensions used in table II.

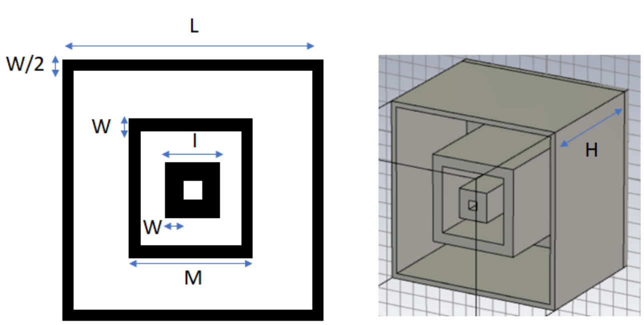


Fig. 8. Metal-Only Phoenix Cell

The reflection phase of the phoenix cell changes accordingly to the central ring length that is variable. The phoenix cell

TABLE II
PHOENIX CELL DIMENSION 14GHZ

Parameters	Value[mm]
L	12
W	0.7
I	2
H	9
M	2-12

starting positions corresponds to $M = 2\ mm$ and increases until it reaches 12 mm, in physical terms, these two situations are exactly the same cell, meaning that the phoenix cell goes back to its initial shape after a whole theoretically 360 phase cycle has been achieved. Different positions for the central ring are shown in figure 9 demonstrating the phoenix cell cycle.

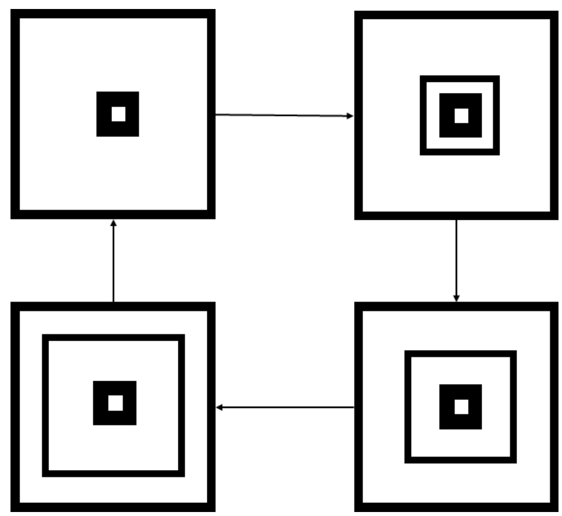


Fig. 9. Phoenix Cell Cycle

Using CST-MWS in the frequency domain solver, the simulated phase responses of the phoenix cell in figure 10 were obtained for a feed with an incident angle of 30°, 45° and 60°.

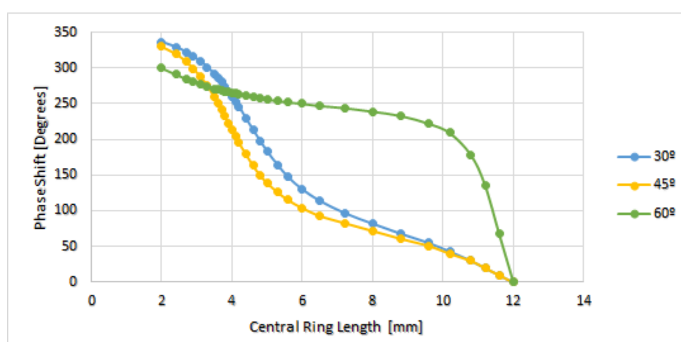


Fig. 10. Simulated phase responses s_{11} of the phoenix cell for an incident angle of 30°,45° and 60° at 14 GHz

The same incident angle of 45° is chosen as before. Figure 11 show the s_{11} amplitude response for the phoenix unit cell. The obtained reflection coefficient has a better $|s_{11}|$ than the slot-type unit cell with stubs since it's virtually almost 0 dB across the band of interest.

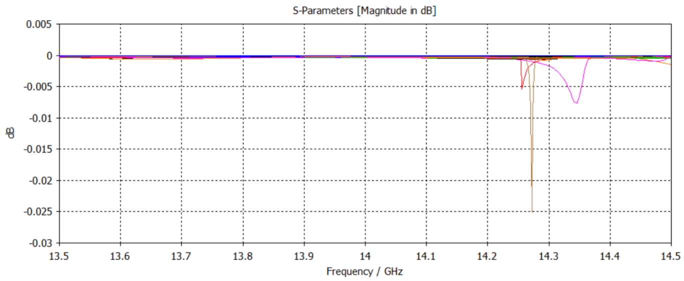


Fig. 11. s_{11} magnitude of the designed phoenix cell for a 45° incident angle. Each color represents a different M length

IV. Reflect-array Design

A. Reflect-array using slot-type unit cell with stubs

In order to design the reflect-array antenna, the results in figure 4 are taken in to account leading to the reflect-array antenna present in figure 12 using the slot-type with stubs unit cell.

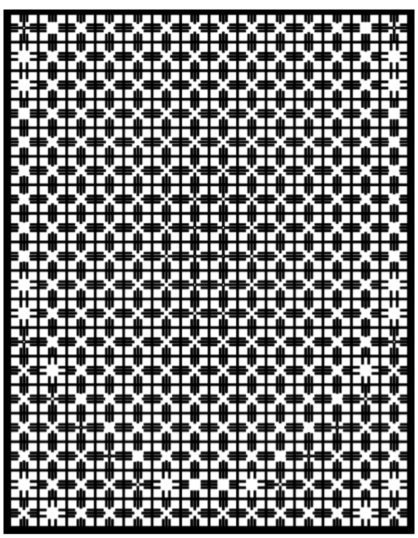
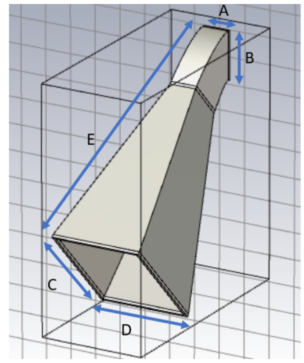


Fig. 12. 2D Model of the reflect-array antenna using slot-type unit cells

A horn antenna feed as seen in figure 13 is used to transmit a radio wave beam to the reflect-array surface with 15.3 dB directivity at 14 GHz, the horn antenna radiation pattern is presented in figure 14.



Parameters	Value [mm]
A	7.9
B	15.8
C	44.85
D	31.5
E	72

Fig. 13. Feed Horn and respective dimensions

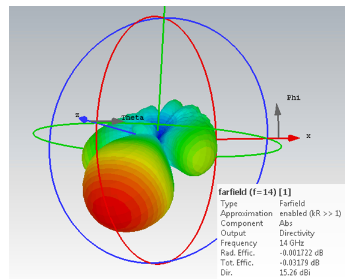


Fig. 14. Horn antenna radiation pattern at 14 GHz

The reflect-array was then simulated using the time domain solver of CST-MWS leading to the following far-field result in figure 15.

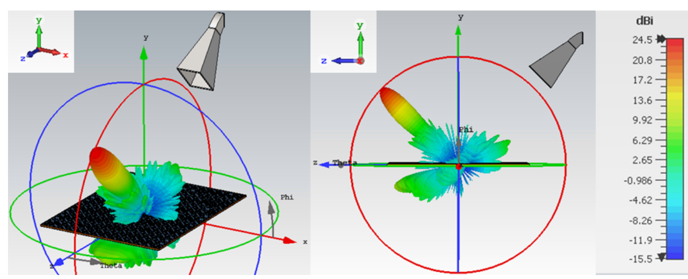


Fig. 15. Simulated radiation pattern result for TE mode (feed in vertical position) for the reflect-array with slot-type unit cells

According to the CST-MWS simulation results, the gain obtained for the full-wave simulation is 24.5 dB for $Theta = 45°$ which is in the vicinity of the predicted directivity calculated in KH3D of 26.1 dB leading to a 1.6 dB difference. The simulations also show -18.6 dB side lobe level that represent the ratio, of the amplitude at the peak of the main lobe to the amplitude at the peak of the second highest side lobe.

For radar applications it's crucial to have a good accurate control of polarization where the simultaneous Horizontal and Vertical polarization can enable two independent communication channels to occupy the same spectral space. In this case with the TE mode, the signal is transmitted with horizontal polarization meaning that a low value for vertical polarization is expected. The co-polarization and cross-polarization radiation pattern for $Phi = 90°$ cut are represented in figure 16 and figure 17 respectively, for $Theta = 45°$ a cross-polarization value of $-100\ dB$ is obtained as expected.

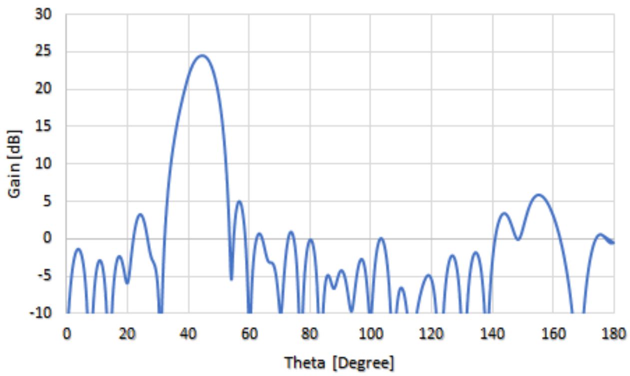


Fig. 16. Co-polarization radiation pattern at 14 GHz for the reflect-array with slot-type unit cell with stubs

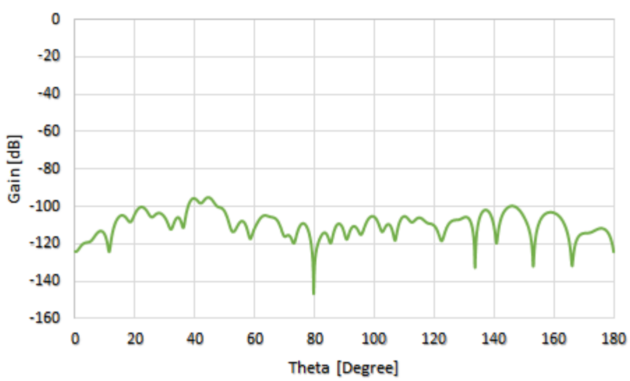


Fig. 17. Cross-polarization radiation pattern at 14 GHz for the reflect-array with slot-type unit cell with stubs

After the incident wave, generated by the horn antenna feed, reflects on the reflect-array surface, the phase corrections are made and an almost perfect planar wave is generated.

In order to guarantee a better altimeter study many radars use two or more different illumination frequencies. By transmitting a succession of pulses with different carrier frequencies, the probability of target detection is increased and therefore more reliable. The received signals can then be separately processed to maintain coherence.

A more in depth analyse of how the gain, directivity, output angle and side lobe levels vary with different frequencies for this reflect-array can be seen in table III.

At 13.5 GHz the realised gain has a drop of 0.8dB and at 14.5 GHz a drop of 1.1 dB when compared to the 14GHz gain, leaving us with a 1 GHz band to use for radar purposes.

TABLE III
FREQUENCY BAND STUDY FOR THE REFLECT-ARRAY COMPOSED OF SLOT-TYPE UNIT CELLS

Frequency	Directivity[dB]	Gain[dB]	Output Angle[Degree]	SLL[dB]
12	17.5	17.4	46	-6.8
12.5	18.6	18.6	45	-7.2
13	21.1	2 1	45	-9.2
13.5	23.8	23.7	45	-13.5
14	24.6	24 .5	45	-18.7
14.5	23.5	23.4	45	-15.8
15	21.1	21	45	-11.3
16.5	19.9	19.8	46	-10.9
16	19.9	19.8	46	-8.9

B. *Reflect-array using phoenix cells*

Using the same procedures has in chapter IV-A a reflect-array antenna using the previous mentioned phoenix cells was created. Figure 18 presents a 2D top view of the reflect-array antenna.

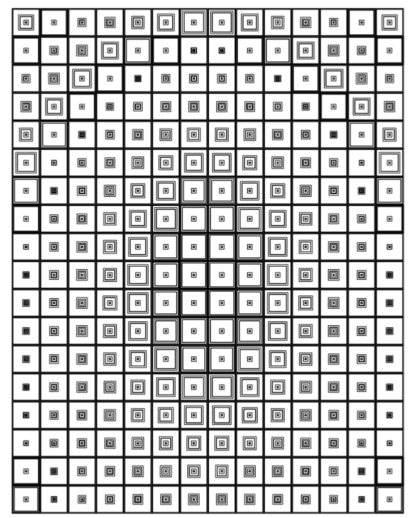


Fig. 18. 2D Model of the reflect-array antenna using phoenix unit cells

Using the same horn feed antenna as in figure 13 with 15.3 dB directivity for the central frequency of 14 GHz, the reflect-array antenna was simulated using the time domain solver of CST-MWS leading to the following far-field results in figure 19.

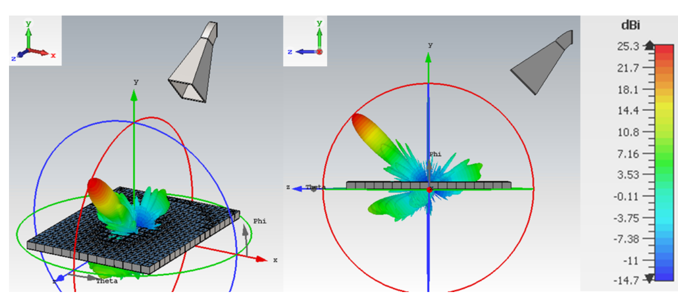


Fig. 19. Simulated radiation pattern result for TE mode (feed in vertical position) for the reflect-array with phoenix cells

According to the CTS-MWS simulation results, the gain obtained for the full-wave simulation is 25.34 db for $Theta =$

45° which is more closer to the KH3D calculated directivity of 26.1 dB than the previous tested reflect-array antenna using slot-type unit cells with stubs, and a side lobe level of -17.4 dB.

As mentioned before, for radar applications it is crucial to have a good accurate control of polarization. The transmitted signal has a horizontal polarization and therefore a low value for the vertical polarization is expected. Figure 20 and figure 21 present the co-polarization and cross-polarization radiation pattern respectively for a $Phi = 90°$ cut.

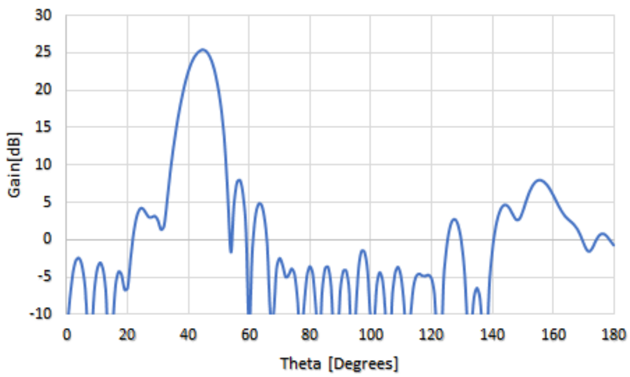


Fig. 20. Co-polarization radiation pattern at 14 GHz for the reflect-array with phoenix cell

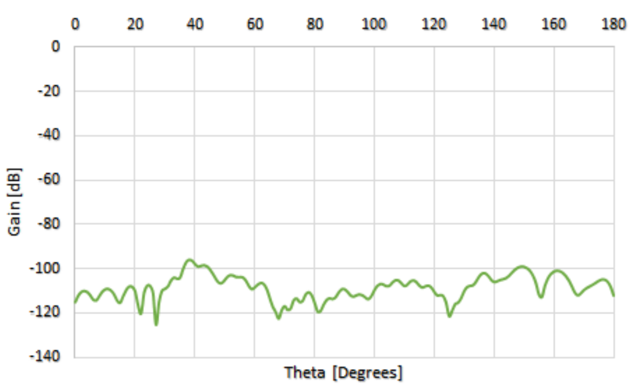


Fig. 21. Cross-polarization radiation pattern at 14 GHz for the reflect-array with phoenix cell

A more in depth analyse of how the gain, directivity, output angle and side lobe levels vary with different frequencies for this reflect-array can be seen in table IV

TABLE IV
FREQUENCY BAND STUDY FOR THE PHOENIX CELL REFLECT-ARRAY

Frequency	Directivity[dB]	Gain[dB]	Output Angle[Degree]	SLL[dB]
12	15.5	15.5	46	-2.3
12.5	18.1	18.1	45	-4.9
13	21.6	21.6	45	-8.8
13.5	24.3	24.3	44	-13.2
14	25.3	25.3	45	-17.4
14.5	25.2	25.2	45	-16.2
15	24.4	24.4	45	-11.4
16.5	23.6	23.6	46	-8.5
16	22.5	22.5	46	-7.7

At 13.5 GHz the realised gain has a drop of 1.14 dB and at 14.5 GHz a drop of 0.1 dB when compared to the 14 GHz gain, leaving us with a 1 GHz band to use for radar purposes.

1) Phoenix Unit Cell versus Slot-type Unit Cell with Stubs: In the previous chapters, two reflect-array antennas were designed and simulated. Figure 22 shows a direct comparison of the obtain gain for the two reflect-array antennas at the central frequency of 14 GHz.

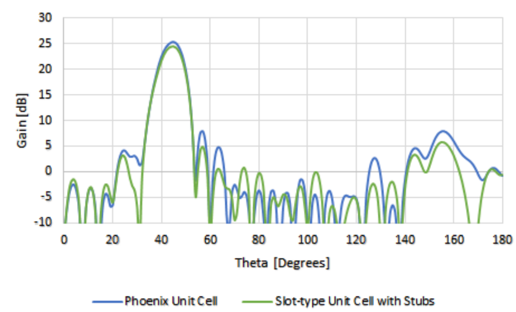


Fig. 22. Co-polarization radiation pattern at 14 GHz comparison for the reflect-array using Phoenix unit cells and Slot-type unit cells with stubs

As it is possible to verify the two curves are very similar, being the more noticeable differences, the main lobe gain that is 0.8 dB bigger in the phoenix cell reflect-array and on the other hand the side lobe level is better for the slot-type unit cell with stubs since the secondary lobes are in the majority inferior to the ones in the phoenix antenna. Both results were in the expected range of the previous calculations using KH3D, that speculated a direct gain of approximately 26 dB for an antenna of these dimensions. The phoenix unit cells were introduced has a solution for a more smooth phase transitions in order to counter the jumps in 360° cycles. The reflect-array with phoenix cells did indeed present better simulated values, but not significantly better to justify using one over the other.

The two reflect-arrays designed in the previous chapter, have one main difference, that is the best way to fabricate an antenna prototype for the reflect-arrays.

In the case of the slot-type unit cell with stubs, since it is made of a grounded plane and a sheet of metal in which the unit cells will be, the best way to make a prototype will be through the use of a technique called chemical etching.

For the phoenix unit cell reflect-array, the best way to fabricate a prototype, taking in to account the limitations of the reflect-array and it being a single piece, is through 3D metal printing. A metal 3d printer utilizes a laser beam to melt layers of metal powder on top of each other. This additive process allows metal parts to be grown out of a bed of powdered metal.

The main difference of this technologies from a client point-of-view, is the fabrication cost. Since chemical etching is a faster and much cheaper solution, the reflect-array with slot-type unit cells with stubs was chosen to be integrated in the NANOSTAR project.

C. Reflect-array study for radar applications

With the intention to understand if the reflect-array antenna designed and simulated on the previous subsection IV-A can be used for the NANOSTAR flyby secondary mission for an altimetry study, the maximum range of the antenna needs to be determined.

Using the equation 8 where:

- $P_t = 10\ W$
- $G = 24.5\ dBi$
- $\sigma = 1.06926 * 10^8$
- $\lambda = 0.02141375\ m$
- $P_{min} = 10^{-13}\ W$

The considered satellite footprint radius in the moon surface can be calculated with equation 17.

$$S_R = \tan\theta R_i \Rightarrow S_R = \tan(6.4381°)90000[m] \tag{17}$$
$$\Rightarrow\ S_R = 10\ 155.7\ m$$

The radar maximum range will then be:

$$R_{max} = \left[\frac{P_t G^2 \sigma \lambda^2}{(4\pi)^3 P_{min}}\right]^{1/4} \Rightarrow R_{max} = 140\ 722\ m \tag{18}$$

The result in equation 18 show that the Cubesat can detect a reflected signal of $10^{-13}\ W$ to a maximum range of $140.722\ km$ from the moon surface.

The NANOSTAR project is designed for a periselenium pass lower than $100\ km$, which means that has long as the received signal can be atleast $10^{-13}\ W$, the cubesat will be able to work as a radar and detect the echo signal.

V. Conclusion

The main objective for this thesis is the creation of a reflect-array antenna, capable of providing a linear polarized, high gain antenna solution for the K_u band, that can be integrated into a 6U Cubesat in the NANOSTAR moon flyby mission. The main objective of the mission is to retrieve science data in the form of lunar surface photographs, in this thesis a secondary mission with the objective of mapping the moon surface with altimetry data studies was presented. For this mission a planar antenna of the type reflect-array was designed for the K_u band at a central frequency of $14\ GHz$.

Cubesats have a limited size that does not allow carrying too complex scientific instruments, leading to some limitations in the reflect-array antennas dimensions. The 6U Cubesat available for this mission will have a periselenium pass lower than $100\ km$ and have a limited power supply to the antenna that needs to be taken into account to make sure that the antenna is capable of transmitting and receiving the reflected signal for this distance.

The proposed reflect-array antenna uses all-metal unit cells, to make the design compatible with other Earth orbit missions, where dielectric based antennas might be susceptible to electrostatic charge buildup and arcing.

In this thesis two different metal-only unit cells were designed. At first a slot-type unit cell with stubs was modified from an existing model enabling it to achieve a higher phase range. This unit cell represented one negative aspect relating to the coupling effects with the electromagnetic interaction between the antenna elements in the array. To solve this problem, another unit cell using phoenix elements was designed. The phoenix cell eliminates the existence of sharp phase transitions, meaning that the cell had smooth transitions when a jump of 360° was required, improving the degradation's in the array pattern.

To better accommodate the insertion of the reflect-array antenna and feed horn antenna in the 6U Cubesat, a 45° incident angle was chosen so that the reflect-array could be placed in the base of the Cubesat with a horn antenna feed pointing directly at its center.

Before the creation of the two reflect-array antennas using the before mentioned unit cells, some preliminary simulations were made in KH3D. The simulations results, showed a maximum theoretical directivity of $28.4647\ dB$ and expected directivity of $26.1\ dB$ for an antenna with a total dimension of $216x168\ mm^2$ and a central frequency of $14\ GHz$. Using CST-MWS for the reflect-array antenna composed of slot-type unit cells with stubs simulation, resulted in a $24,5\ dB$ gain in the main lobe direction with a side lobe level of $-18.6\ dB$. This reflect-array antenna showed good measurements for $13.5\ GHz$ and $14.5\ Ghz$ allowing a frequency band of $1\ GHz$ to be used for radar purposes.

The simulations for the reflect-array antenna composed of the phoenix unit cells, showed a $25.3\ dB$ gain in the main lobe direction with a side lobe level of $-17.4dB$. This reflect-array also showed good measurements for $13.5\ GHz$ and $14.5\ GHz$ allowing for a frequency band of $1\ GHz$ to be used.

It was possible to verify that the two designed reflect-array antennas worked very similarly, but the phoenix cell elements produced a higher gain than the slot-type unit cells. Taking into account the design of the two reflect-arrays it was determined that the phoenix type reflect-array should be manufactured using 3D metal printing and that the slot-type unit cell with stubs should be manufactured using chemical etching techniques. Due to this, the slot-type unit cell was chosen to incorporate the NANOSTAR cubesat since it represented a much lower production cost than the 3D metal printing option of the Phoenix cells.

Having defined the reflect-array to be used, an altimetry study was made taking into account the measurements of the reflect-array antenna. It was determined that the reflect-array could tansmit and receive the echo signal to a distance of $114\ 702\ m$, making this antenna viable for altimetry studies. A basic Mathematica code was then developed to test prove that a s_{11} measured signal by the reflect-array could indeed be analyzed, and the range of the Cubesat to the moon surface obtained.

VI. Future Work

The slot-type unit cell with stubs reflect-array antenna was designed and fulfills all the strict mission and component requirements. This does not mean that further improvements cannot be made.

For the K_u band the reflect-array antenna presented very good theoretical performance, but no real prototype was created and properly tested [1]. It is necessary to produce a prototype to be tested in an anechoic chamber to further validated the simulated results obtained thought out this thesis.

It was proven with the phoenix cells that the reflect-array gain can be closer to the theoretical gain calculated with KH3D. Further unit cells should be tested, with the objective of creating a reflect-array antenna with a better gain than the slot-type unit cells, and with a manufactured cost closer to them. One possible solution could be the re-design of the phoenix cell reflect-array that would not involve using 3D printing techniques, lowering its production cost but maintaining the reflect-array gain.

The reflect-array developed in this thesis was used for a secondary mission of the NANOSTAR project, for altimetry studies purposes and an adaptation for the main objective of the NANOSTAR project should be developed. To fulfill the main objective the reflect-array antenna should be able to work for SAR applications that is a form of radar that is used to create two-dimensional images or three-dimensional reconstructions of objects, such as the moon surface.

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[1] Due to unforeseen external reasons, it wasn't possible to have access to the laboratory to produce and test the prototype of the reflect-array antenna