All-metal Reflectarray Antenna Design
(11-02)

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Content

1. Abstract

In the world of antennas, there are multiple types of antennas, each with their advantages and disadvantages. Today, reflectarray is one of the most favoured antennas in the world. In this report, we will be discussing the reflectarray antenna. This project aims to explore and design a reflectarray. A reflectarray comprises printed elements of different phases that have to be appropriately arranged in a periodic grid to control the radiation of the electromagnetic (EM) field incident on it. For this project, we wish to design and build an efficient low-loss all-metal reflectarray antenna. We also hope to develop code(s) to predict the radiation pattern of a reflectarray antenna.

Through a theoretical approach, we find the phase shift needed for each element. With the phase shifts and a program that we have developed, we can compute the radiation pattern of this idealised reflectarray. In a parallel effort, we also derived the phase shift as a function of element dimension (S-curve) using a commercial EM software. With the S-curve and required phase shift, we calculate the specific dimensions of the different printed elements of the reflectarray. This reflectarray is then simulated in the same commercial EM software to obtain its radiation pattern. Afterwhich, we would compare it with the idealised reflectarray.

2. Introduction

2.1 What Exactly is a Reflectarray Antenna?

It is a class of directive antennas in which multiple driven elements are mounted in front of a flat surface designed to reflect the radio waves in the desired direction. It has evolved to mitigate the disadvantages associated with either the parabolic reflector or the conventional array. Figure 2.1.1 and 2.1.2 show how the antenna works.

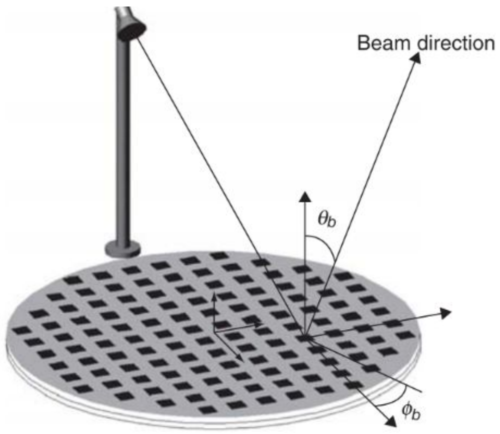

Figure 2.1.1 Typical geometry of a printed reflectarray antenna

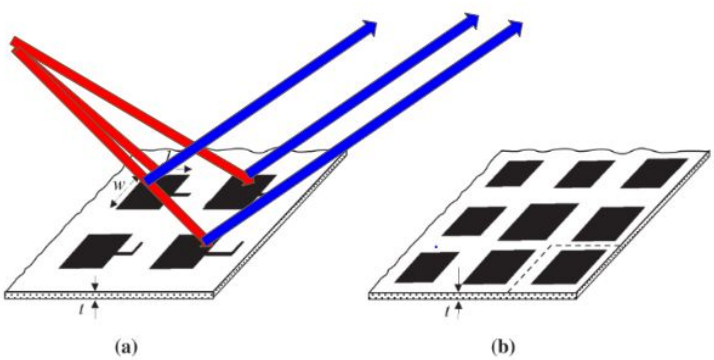

Figure 2.1.2 Phasing elements in printed reflectarrays. (a) Rectangular patches with attached stubs. (b) Rectangular patches of varying size.

2.2 Problems related to reflectarray antenna

There are two problems related to the reflectarray antenna. The first problem is the bandwidth that is limited by element. The microstrip patch element generally has a bandwidth of about 3 to 5 per cent. To achieve wider bandwidth for a conventional microstrip array, techniques such as using the thick substrate for the patch, stacking multiple patches.

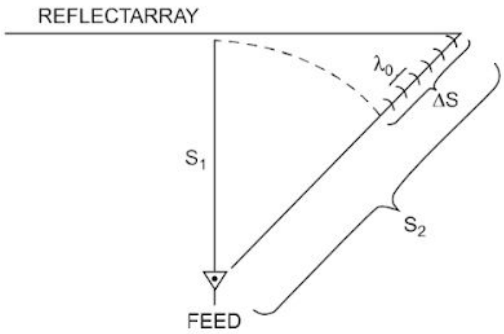

Figure 2.2.1

The second problem is the Bandwidth Limited by Differential Spatial Phase Delay. Referring to Figure 2.2.1, the differential spatial phase delay, ΔS, is the phase difference between the two paths S1 and S2 from the feed to the reflectarray elements. ΔS can be many multiples of the wavelength (λ), $\Delta S = (N + d)\lambda$ where N is an integer and d is a fractional number of a free space wavelength λ. As the frequency changes, the factor $(N + d)\lambda$ becomes $(N + d)(\lambda+\Delta\lambda)$. The amount of phase change in each path when compared with a reference path, say S1, is $(N + d)\Delta\lambda$ which can be a significant portion of a wavelength or 360°.

2.3 Possible Applications

Applications include usage in satellite communications, contoured beam space antennas, cloud or precipitation radars, beam scanning and amplification reflectarrays, in addition to defence and commercial uses.

With low mass, low profile, and a comfortable fabrication and transport process, reflectarray antennas are advantageous for use despite their narrow bandwidth, which is controlled by the phase values of the elements. They are easy for circuitry integration, and each element's phase functions can be individually controlled. An increase in the number of same-size elements used results in a larger antenna compared to the wavelength, ultimately leading to a higher gain and, therefore, a narrower beamwidth of the antenna's main lobe.

A narrower beamwidth of the antenna's main lobe optimises the capability of the reflectarray antenna by increasing its efficiency and several other factors that affect the functionality of the reflectarray antenna. Hence, enabling small satellites to transfer high volume data between one another in low-Earth orbit or even in orbit around the Moon.

It is pertinent to solve this problem as there is a prevalent problem of dielectric loss in the reflectarray antenna, hence lower loss is desired for higher radiation efficiency. Our solution would be to have very thin/no dielectric substrate or all-metal, and possibly 3-D print to reduce weight.

In this project, we will focus on designing a reflectarray with 15 x 15 = 225 elements.

3. Solution Design

3.1 Information gathering on reflectarray

The authors (John Huang and José A. Encinar) discuss numerous aspects of the reflectarray, such as its advantages and disadvantages (Bandwidth Limited by Element and Bandwidth Limited by Differential Spatial Phase Delay).

The authors also describe and introduce the reflectarray antenna. They describe the reflective array antennas as many identical driven elements, fed in phase, in front of a flat, electrically large reflecting surface to produce a unidirectional beam of radio waves, increasing antenna gain and reducing radiation in unwanted directions. The reflector may be a metal sheet or more commonly a wire screen.

Advantages of the reflectarray antenna include low losses, ease of manufacture in flat panels, low cross-polarization and the possibility of electronic control of the beam. Disadvantages are bandwidth limited by element and differential spatial phase delay.[1] The authors, John Huang and José A. Encinar also went to discuss and explain about the development history of reflectarray and made comparisons with modern technology in another chapter.[2]

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[1] Huang, J., & Encinar, J. A. (2008). Reflectarray antennas - Chapter 1 Introduction to Reflectarray Antenna Retrieved March 17 2020, Institute of Electrical and Electronics Engineers: John Wiley & Sons.

[2] Huang, J., & Encinar, J. A. (2008). Reflectarray antennas - Chapter 2 Development History Retrieved March 17 2020, Institute of Electrical and Electronics Engineers: John Wiley & Sons.

3.2 Equations governing the reflectarray antenna

The authors, John Huang and José A. Encinar, also discussed the different equations needed to formulate a reflectarray antenna. Based on these equations, we can then better understand the way the reflectarray antenna works.[3]

Equation 1: Phase Shift

$$\boxed{\phi_R = k_0(d_i - (x_i \cos\varphi_b + y_i \sin\varphi_b)\sin\theta_b)}$$

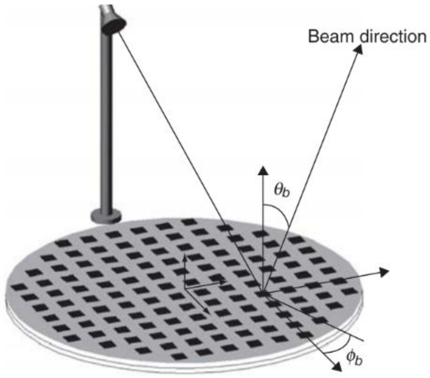

Figure 3.2.1 Typical geometry of a printed reflectarray antenna

In this Equation 1, $k_0 = 2\pi/\lambda$ (wave propagation constant), d_i: the distance between the horn and reflectarray elements, x_i and y_i: coordinates of the elements on the reflectarray, and $\mathbf{\Phi}_b$ and $\boldsymbol{\theta}_b$: the direction of the desired beam in spherical coordinates (Figure 3.2.1).

This equation forms the basic understanding of the reflectarray antenna phase beaming, and it determines the direction of the signal after it is reflected.

k_0d_i cancels the phase traversed by the wave from feed to element, and the remaining equation steers the wave to the desired direction (based on phased array theory). The subject of this equation (Phi_R) is the phase shift at each element.

[3] Huang, J., & Encinar, J. A. (2008). Reflectarray antennas - Chapter 3 Antenna Analysis Technique Retrieved March 17 2020, Institute of Electrical and Electronics Engineers: John Wiley & Sons.

Equation 2: Field Calculation of x-polarised feed

$$\bar{E}_\theta(\theta,\varphi) = \frac{jke^{-jkr}}{2\pi r}[\hat{\theta}C_E(\theta)\cos\varphi - \hat{\varphi}C_H(\theta)\sin\varphi]$$

In the equation, C_E and C_H are defined as powers of q. Both C_E and C_H are determined by the E and H-plane patterns of the feed horn.

$C_E(\boldsymbol{\theta}) = \cos^{qE}(\boldsymbol{\theta})$ and C^H $(\boldsymbol{\theta}) = \cos^{qH}$ $(\boldsymbol{\theta})$. An axial symmetric pattern of the array is usually desirable. Therefore, the same q will be chosen in both planes, where $q_E = q_H = q = 1$.

3.3 Solution Criteria

1) The type of material used:
    a) What metallic element? Is a metallic compound or an alloy better?
    b) Electroplate a plastic or 3D print the metal?
2) Type of array used:
    a) What type (Shape/Structure) of array?
    b) How many arrays in one antenna?
3) Type and number of elements (Reflectors) used:
    a) What type (Shape/Structure) of reflectors?
    b) How many reflectors will there be in one antenna?
4) We will also think about the Strength, Intensity and Frequency of Radio Signals:
    a) How big should the antenna be?
    b) Can the metallic element added to the antenna allow the antenna to receive low-frequency and low-intensity radio waves or signals?
    c) Required gain affects the size of the array.
    d) Power handling affects element design.

3.4 Proposed Solution Design (Figure 3.4.1)

- The proposed solution design will contain fully metallic elements capable of handling high power.
- The proposed solution design will contain an all-metal element with at least 360° phase range.

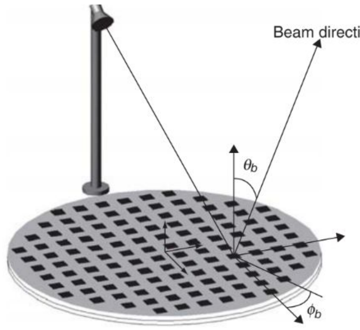

Figure 3.4.1

3.5 Usage of Different tools

➢ These are the programming languages we used:

1) We used Python to compute required element phases for desired beam direction and predict radiation pattern of reflectarray
2) C++ and C were used as an alternative when using Python became tedious.

➢ The tools we used include AutoCAD, CST and Excel/MATLAB:

1) We used AutoCAD to create our waveguides.
2) We also used the CST Studio Suite to analyse electromagnetic fields and optimise our antenna design.
3) We also used Excel/MATLAB as it lets us design, visualise, and analyse antennas in the Antenna Toolbox library interactively.

3.6 Design Process

The general procedural steps are as follows:

1) Through Python and Excel/MATLAB, we obtain the phase shifts required at the various element positions.
2) CST MWS is used to obtain the S-curve at the desired operating frequency of the reflectarray (10GHz).
3) From the results of the above two steps, the dimensions for each element on the array can be determined.
4) The reflectarray with the different element dimensions and positions is quickly drawn in AutoCAD through the running of a script. (We have completed till this stage.)
5) The array elements are then hatched and exported in .dxf file format.
6) The .dxf file can be imported into CST MWS for the simulation of the radiation pattern.
7) We can also predict the radiation gain pattern of the reflectarray, which is used for comparison with the results from CST MWS.

3.6.1 Phase Shift at every element

```
import math
def main():
  k_nott = 2*(math.pi)/(3*(10**8)/(10**9))
  φb = 0 # in degree(60)
  φb = φb*(math.pi)/180
  θb = 0 # in degree(1.4)
  θb = θb*(math.pi)/180

  #antenna coordinates
  xa = 0
  xa = (xa)*(10**(-2))
  ya = 0
  ya = (ya)*(10**(-2))
  za = 30
  za = (za)*(10**(-2))

  for xi in range (-14, 15, 2):
    xi = (xi)*(10**(-2))
    for yi in range (-14, 15, 2):
      yi = (yi)*(10**(-2))
      di = math.sqrt((xi)**2 + (yi)**2 + (za)**2)
      #3D Distance

      ϕR = k_nott*(di-(xi*math.cos(φb) + yi*math.sin(φb))*math.sin(θb))
      ϕ = -k_nott*di + ϕR
      ϕR_new = ϕR%(2*math.pi)
      ϕR_new = ϕR_new*(180/math.pi)
      #converts to degrees for easy reading
      print(xi, " ", yi, " ", ϕR_new)
main()
```

We used 0 for both values of Phi and theta to start us off: We can easily replicate our whole process for other values too!

Figure 3.6.1.1

Using Python, we created this code (Figure 3.6.1.1) to generate the data points for the surface plot. In this code, we generated the phase shifts at every point on our 31cm by 31cm array. We set the feed horn to be 30cm above our reflectarray, and the values of Phi and Theta to be 0 degrees. This enabled us to generate 225 data points, corresponding to 225 coordinates on the reflectarray. We have set the separation between elements to be 2cm.

These are snippets of the data (shown below) generated from the code (Figure 3.6.1.2).

```
-0.14   -0.14   71.3328181346743
-0.14   -0.12   62.563604679816216
-0.14   -0.1   54.99879517897402
-0.14   -0.08   48.705272782233614
-0.14   -0.06   43.7424921902573
-0.14   -0.04   40.15996801279364
-0.14   -0.02   37.99497484264796
-0.14   0.0   37.27068857392437
-0.14   0.02   37.99497484264796
-0.14   0.04   40.15996801279364
-0.14   0.06   43.7424921902573
-0.14   0.08   48.705272782233614
-0.14   0.1   54.99879517897402
-0.14   0.12   62.563604679816216
-0.14   0.14   71.3328181346743
-0.12   -0.14   62.563604679816216
-0.12   -0.12   53.60851055073807
-0.12   -0.1   45.876828606906344
-0.12   -0.08   39.43960745023768
-0.12   -0.06   34.36024140371963
-0.12   -0.04   30.691694306392964
```

Figure 3.6.1.2[4]

[4] Read the Columns from Left to Right
1st Column: X_i , 2nd Column: Y_i and 3rd Column: Phi_R

	-0.14	-0.12	-0.1	-0.08	-0.06	-0.04	-0.02	0	0.02	0.04
-0.14	71.333	62.564	54.999	48.705	43.742	40.16	37.995	37.271	37.995	40.16
-0.12	62.564	53.609	45.877	39.44	34.36	30.692	28.474	27.732	28.474	30.692
-0.1	54.999	45.877	37.995	31.428	26.243	22.497	20.232	19.473	20.232	22.497
-0.08	48.705	39.44	31.428	24.749	19.473	15.659	13.352	12.58	13.352	15.659
-0.06	43.742	34.36	26.243	19.473	14.123	10.254	7.913	7.1294	7.913	10.254
-0.04	40.16	30.692	22.497	15.659	10.254	6.3441	3.978	3.1859	3.978	6.3441
-0.02	37.995	28.474	20.232	13.352	7.913	3.978	1.5965	0.7991	1.5965	3.978
0	37.271	27.732	19.473	12.58	7.1294	3.1859	0.7991	0	0.7991	3.1859

Figure 3.6.1.3[5]

Based on the 225 data points of Phi_R generated, we created a database of Phi_R in an excel spreadsheet. Above is a snapshot of a part of this database (Figure 3.6.1.3). We realised that Excel has a contour function to plot out the surface plot of the array, making it easier to obtain the plot. Below is the corresponding surface plot we have found via Excel (Figure 3.6.1.4).

	-0.14	-0.12	-0.1	-0.08	-0.06	-0.04	-0.02	0	0.02	0.04	0.06	0.08	0.1	0.12	
-0.14	71.333	62.564	54.999	48.705	43.742	40.16	37.995	37.271	37.995	40.16	43.742	48.705	54.999	62.564	71.333
-0.12	62.564	53.609	45.877	39.44	34.36	30.692	28.474	27.732	28.474	30.692	34.36	39.44	45.877	53.609	62.564
-0.1	54.999	45.877	37.995	31.428	26.243	22.497	20.232	19.473	20.232	22.497	26.243	31.428	37.995	45.877	54.999
-0.08	48.705	39.44	31.428	24.749	19.473	15.659	13.352	12.58	13.352	15.659	19.473	24.749	31.428	39.44	48.705
-0.06	43.742	34.36	26.243	19.473	14.123	10.254	7.913	7.1294	7.913	10.254	14.123	19.473	26.243	34.36	43.742
-0.04	40.16	30.692	22.497	15.659	10.254	6.3441	3.978	3.1859	3.978	6.3441	10.254	15.659	22.497	30.692	40.16
-0.02	37.995	28.474	20.232	13.352	7.913	3.978	1.5965	0.7991	1.5965	3.978	7.913	13.352	20.232	28.474	37.995
0	37.271	27.732	19.473	12.58	7.1294	3.1859	0.7991	0	0.7991	3.1859	7.1294	12.58	19.473	27.732	37.271
0.02	37.995	28.474	20.232	13.352	7.913	3.978	1.5965	0.7991	1.5965	3.978	7.913	13.352	20.232	28.474	37.995
0.04	40.16	30.692	22.497	15.659	10.254	6.3441	3.978	3.1859	3.978	6.3441	10.254	15.659	22.497	30.692	40.16
0.06	43.742	34.36	26.243	19.473	14.123	10.254	7.913	7.1294	7.913	10.254	14.123	19.473	26.243	34.36	43.742
0.08	48.705	39.44	31.428	24.749	19.473	15.659	13.352	12.58	13.352	15.659	19.473	24.749	31.428	39.44	48.705
0.1	54.999	45.877	37.995	31.428	26.243	22.497	20.232	19.473	20.232	22.497	26.243	31.428	37.995	45.877	54.999
0.12	62.564	53.609	45.877	39.44	34.36	30.692	28.474	27.732	28.474	30.692	34.36	39.44	45.877	53.609	62.564
	71.333	62.564	54.999	48.705	43.742	40.16	37.995	37.271	37.995	40.16	43.742	48.705	54.999	62.564	71.333

Figure 3.6.1.4

[5] ***Legend:***
Column Labels: X_i (in metres)
Row Labels: Y_i (in metres)
Gradient Plot Phi_R(in degrees)

3.6.2 Use of CST and AutoCAD to consolidate the Solution Design

The CST is used to simulate the waveguide by varying the different height of the piston that is holding up the element in the reflectarray in the waveguide. This is done to find the phase shift of that specific waveguide at that specific height. After finding the phase shift for each respective waveguide, we will plot a phase shift curve and the strength of the electric field curve. Finally, we will use these curves to assist us with the creation of the 225 elements in AutoCAD.

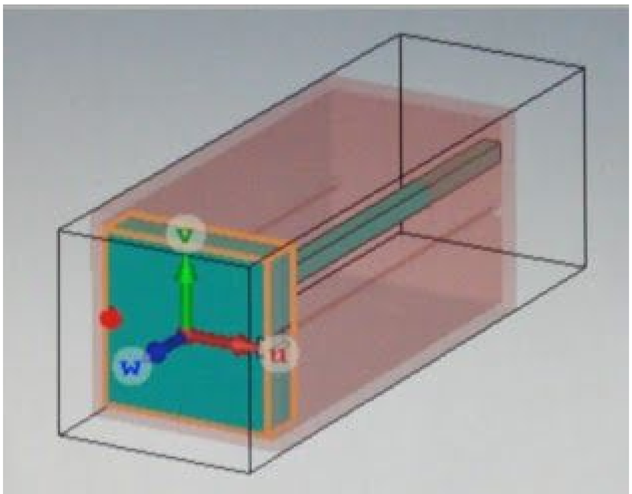

Figure 3.6.2.1

Figure 3.6.2.1 is the design of our platform (the structure coloured blue) with preset variables and coordinates. The platform is set to be 1.8cm by 1.8cm. One platform holds up one element in the reflectarray. The platform is a combination of three different shapes to give a unique shape where there are two rails (one on each side). There is also a piston connected to the platform that will move the platform up and down.

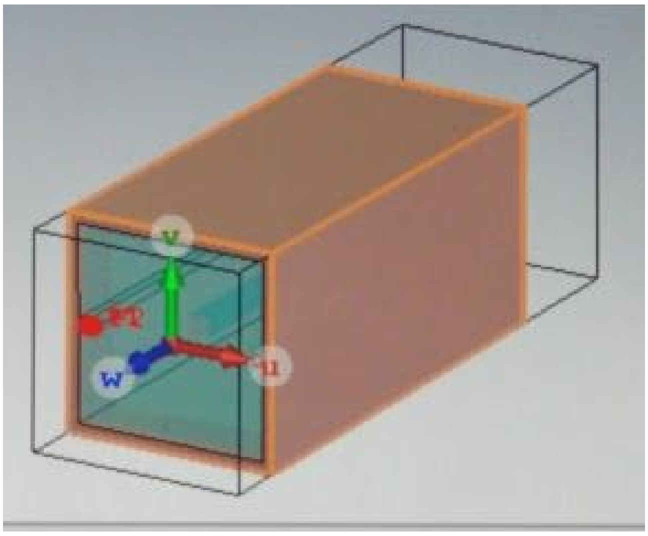

Figure 3.6.2.2

Figure 3.6.2.2 is the design of our wall (the structure coloured orange) with preset variables and coordinates. The external wall is 2.0 cm by 2.0 cm. Inner wall is 1.9cm by 1.9cm (wall thickness is accounted for). Wall is a combination of three different shapes where there are two protruding segments (one on each side) which is encircled by the blue circle. This is the previously mentioned rail. Figure 3.6.2.3 (shown below) is the top view of one waveguide (square).

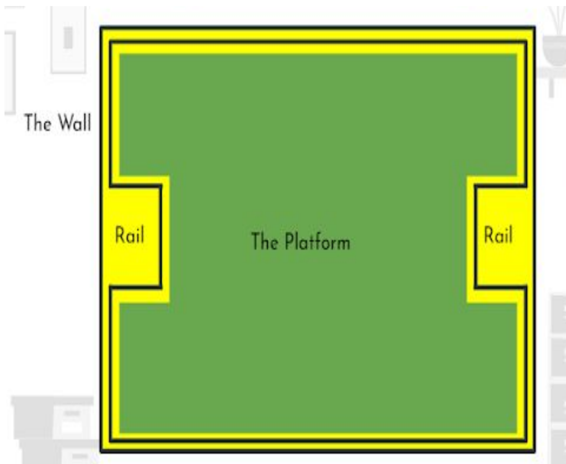

Figure 3.6.2.3

Our simulation calculated 400 corresponding phase values by adjusting the height of the platform from 0 to 40mm by incrementing by 0.1mm. Hence, a graph of phase value

(Figure 3.6.2.4) and the strength of the reflected electric field (Figure 3.6.2.5) can be calculated. The objects were made of PEC[6] (Metal).

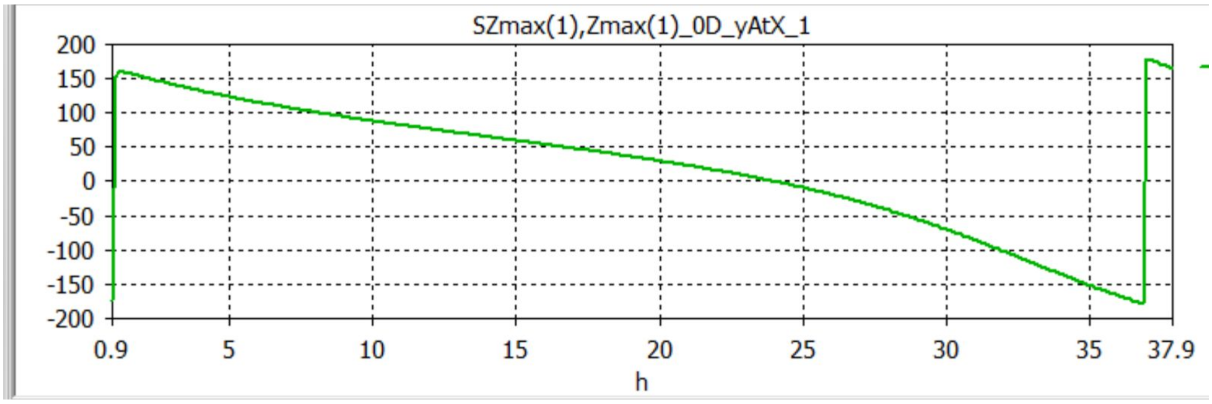

Figure 3.6.2.4 Y-axis is Phase/deg , X-axis is Height/mm

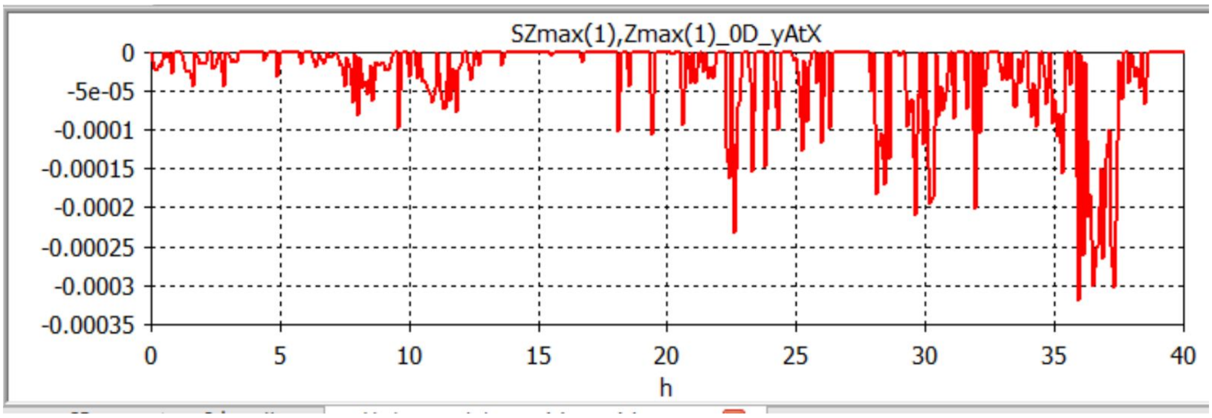

Figure 3.6.2.5 Y-axis is dB, X-axis is Height/mm

[6]Perfect Electric Conductor

Based on the waveguide cross-section dimensions and the S-curve (Figure 3.6.2.4), we can determine the required phase (Figure 3.6.2.7) and corresponding height of the platform (Figure 3.6.2.6) for each element.

AutoCAD was used to generate the platforms shown in Figure 3.6.2.6.

The difference in the platform heights is quite small (the maximum difference is about 8mm) with an overall concave surface.

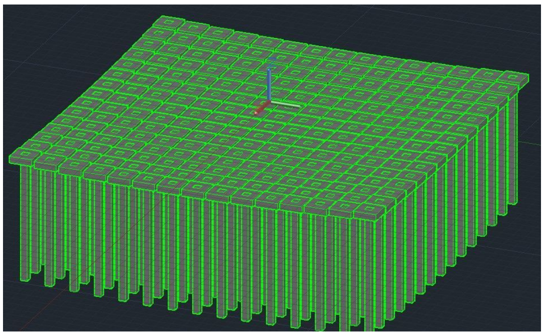

Figure 3.6.2.6

	-0.14	-0.12	-0.1	-0.08	-0.06	-0.04	-0.02	0	0.02	0.04	0.06	0.08	0.1	0.12	
-0.14	71.333	62.564	54.999	48.705	43.742	40.16	37.995	37.271	37.995	40.16	43.742	48.705	54.999	62.564	71.333
-0.12	62.564	53.609	45.877	39.44	34.36	30.692	28.474	27.732	28.474	30.692	34.36	39.44	45.877	53.609	62.564
-0.1	54.999	45.877	37.995	31.428	26.243	22.497	20.232	19.473	20.232	22.497	26.243	31.428	37.995	45.877	54.999
-0.08	48.705	39.44	31.428	24.749	19.473	15.659	13.352	12.58	13.352	15.659	19.473	24.749	31.428	39.44	48.705
-0.06	43.742	34.36	26.243	19.473	14.123	10.254	7.913	7.1294	7.913	10.254	14.123	19.473	26.243	34.36	43.742
-0.04	40.16	30.692	22.497	15.659	10.254	6.3441	3.978	3.1859	3.978	6.3441	10.254	15.659	22.497	30.692	40.16
-0.02	37.995	28.474	20.232	13.352	7.913	3.978	1.5965	0.7991	1.5965	3.978	7.913	13.352	20.232	28.474	37.995
0	37.271	27.732	19.473	12.58	7.1294	3.1859	0.7991	0	0.7991	3.1859	7.1294	12.58	19.473	27.732	37.271
0.02	37.995	28.474	20.232	13.352	7.913	3.978	1.5965	0.7991	1.5965	3.978	7.913	13.352	20.232	28.474	37.995
0.04	40.16	30.692	22.497	15.659	10.254	6.3441	3.978	3.1859	3.978	6.3441	10.254	15.659	22.497	30.692	40.16
0.06	43.742	34.36	26.243	19.473	14.123	10.254	7.913	7.1294	7.913	10.254	14.123	19.473	26.243	34.36	43.742
0.08	48.705	39.44	31.428	24.749	19.473	15.659	13.352	12.58	13.352	15.659	19.473	24.749	31.428	39.44	48.705
0.1	54.999	45.877	37.995	31.428	26.243	22.497	20.232	19.473	20.232	22.497	26.243	31.428	37.995	45.877	54.999
0.12	62.564	53.609	45.877	39.44	34.36	30.692	28.474	27.732	28.474	30.692	34.36	39.44	45.877	53.609	62.564
	71.333	62.564	54.999	48.705	43.742	40.16	37.995	37.271	37.995	40.16	43.742	48.705	54.999	62.564	71.333

Figure 3.6.2.7

3.6.3 Proposed Testing, Analyzing, Redesigning and Implementation of Solution Design

Since this is an external project with DSO, we aim to be able to finish all 225 waveguides on AutoCAD and start to 3D Print out all 225 of them and start to test the piston and organize the waveguides in the order we have calculated. Next, we will also create the Feed Horn that will be the one sending out the waves and test whether it works.

After that, we will combine both components and test whether our reflectarray antenna is sufficiently low-loss. Finally, we will try to predict the radiation gain pattern of the reflectarray, which is used for comparison with the results from CST MWS.

We need to make sure that our reflectarray antennas are resistant to extreme heat and extreme cold, able to transfer high volume data, form a strong optical cross-link, lightweight and portable. This is so that the reflectarray antenna can work properly in space exploration and satellite communication.

3.6.4 Creation of a Model using Lego

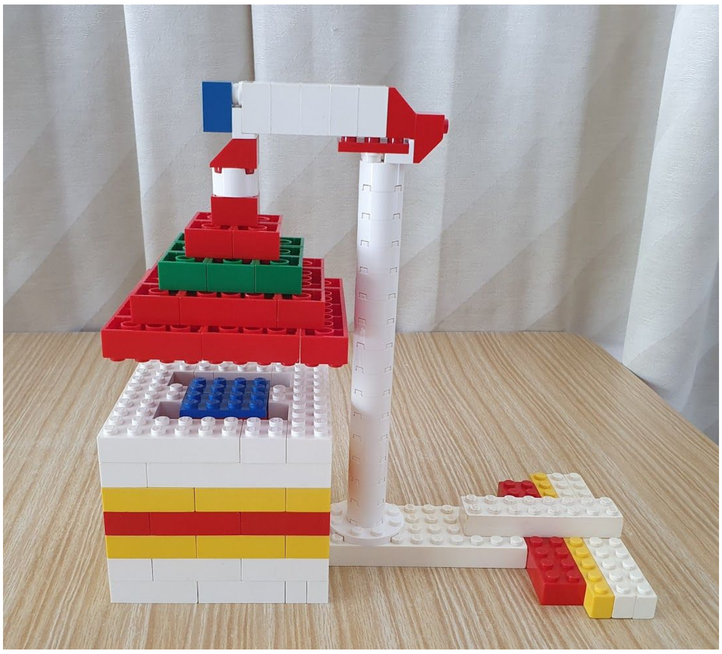

Figure 3.6.4.1

Figure 3.6.4.1 is the lego model of our feed horn (the red lego structure) and the waveguide (the white and yellow lego structure).[7]

7 Disclaimer: A feed horn is bigger than one waveguide in reality. For magnification purposes and better viewing, we have made both equal sizes. Furthermore, there will be multiple waveguides instead of one.

3.6.5 Our Journey

Timeline

14 April: Proposal Evaluation
April-May: Design and Creation of the reflectarray antenna
May-June: Data analysis and representation
June-July: Document results and progress
9 July: Mid-Term Evaluation
July-August: Prepare for the presentation of findings
12 August: Final Evaluation

Workflow

April to May: Use of equations to create several codes for our project to predict radiation pattern of signal
June: Analysis of Code and Graph + Data analysis and representation
June: Using our code and program to design and creation of the reflectarray antenna
July: Document results and progress
July-August: Try to create an actual prototype and prepare for the presentation of findings

Job Scope

Name	Job Scope
Ian Poon (Leader)	Coding of CST Presentation slides (Information) Creating the Written Report
Lucien Leong Guang Shian	Coding of AUTOCAD Crating the Phase Map Presentation slides (Background and Design) Creating the Written Report
Tay Hong Ming	Creation of the Antenna Parts (3D Printing) Presentation slides (Information) Creating the Written Report

4. Results & Discussion

Based on the surface plot obtained and the dimensions we get from the S-curve, we can determine then the exact specifications of each element. We derive the elements' specific position on a Cartesian Graph with the centre of the reflectarray set as (0,0). Furthermore, we also calculated the height of the element from the CST simulation as the different elements have different phase shifts which lead to differing heights in the waveguide itself. We use the CST to simulate a real reflectarray antenna. Using CST, we derive the specific elevation of each element for the reflectarray. It will then aid us in determining the height to match the phase shift for every element.

When proceeding with the solution design to the problem stated, we made sure that our reflectarray antenna can enable multiple missions that currently require large satellites, improve satellite-to-satellite optical communications links in systems that are substantially smaller and simpler, create a robust optical cross-link between the two satellites that is appropriately pointed at and aligned, and increase efficiency and enable small satellites to transfer high volume data between one another in low-Earth orbit or even in orbit around the Moon.

Our findings in this research support the proposed solution to the stated problem as the all-metal reflectarray we created based on the CST simulation has almost zero loss, which is desired for higher radiation efficiency. Our reflectarray elements are also very thin based on our design and are 3D-printed to be all-metal.

For the proposed solution to be implemented to solve the stated problem, we need to take some specific actions. For example, we can make our reflectarray antenna resistant to extreme heat and extreme cold, able to transfer high volume data and to form a strong optical cross-link. We also need to make it lightweight and portable.

5. Conclusion

From this project, we learned how to use different types of software such as CST Studio Suite, AutoCAD and MATLAB, which aided us in the creation and the analysis of our reflectarray antenna. We also learned how to be more independent learners as we go about completing this project as many of these concepts, equations and software are entirely new to us.

This year has been a difficult time, especially since there was the outbreak of COVID-19, disrupting not only our school life but also our project. Due to the implementation of the social distancing measures and circuit breaker measures, we had to adapt to a new normal, a new way to accomplish our project. Since we were unable to meet up with our mentors, both external and internal alike, we needed to have our meetings online via platforms such as Google Meet or Zoom. However, in these different and challenging times, we have persevered and learnt a lot from our experience. We have learnt so much regarding the All-Metal Reflectarray and how to use software like AutoCAD, CST Studio Suite and MATLAB.

6. References

1) Defense Advanced Research Projects Agency (DARPA). (JANUARY 23, 2019). *DARPA prototype reflectarray antenna offers high performance in small package.* Retrieved March 20, 2020 from https://phys.org/news/2019-01-darpa-prototype-reflectarray-antenna-high.html
2) Encinar, José. (2001). Design of two-layer printed reflectarray using patches of variable size. Antennas and Propagation, IEEE Transactions on. 49. 1403 - 1410. 10.1109/8.954929.
3) eoPortal Directory. (n.d.). ISARA (Integrated Solar Array and Reflectarray Antenna). Retrieved March 20, 2020 from https://directory.eoportal.org/web/eoportal/satellite-missions/i/isara
4) Huang, J., & Encinar, J. A. (2008). *Reflectarray antennas - Chapter 1 Introduction to Reflectarray Antenna* Retrieved March 17 2020, Institute of Electrical and Electronics Engineers: John Wiley & Sons.
5) Huang, J., & Encinar, J. A. (2008). *Reflectarray antennas - Chapter 2 Development History* Retrieved March 17 2020, Institute of Electrical and Electronics Engineers: John Wiley & Sons.
6) Huang, J., & Encinar, J. A. (2008). *Reflectarray antennas - Chapter 3 Antenna Analysis Technique* Retrieved March 17 2020, Institute of Electrical and Electronics Engineers: John Wiley & Sons.

7. Acknowledgement

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