

USE OF DIFFERENT ADDITIVE MANUFACTURING METHODS FOR THE
FABRICATION OF AN X-BAND HORN ANTENNA AND ITS COMPATIBILITY
WITH THE MIL-STD-810H STANDARD

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COMPATIBILITY WITH THE MIL-STD-810H STANDARD**

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ABSTRACT

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Additive Manufacturing (AM) is a rapidly developing set of methods with lots of benefits. This technology promises fast, cheap and lightweight fabrication for antennas and waveguides. Different AM technologies such as Fused Filament Fabrication (FFF), Stereolithography (SLA), Material Jetting and Powder Bed Fusion are used to fabricate antennas operating at various frequency bands and provide desirable results. To test the feasibility of the AM technologies for antenna manufacturing and also durability under military environmental conditions, a specific antenna has been modeled and fabricated via FFF, SLA and Metal-FFF type of 3D printers. The FFF and SLA fabricated antennas are electroplated with copper. Thereafter, the radiation parameters of the antennas are measured. The accordance of measurement results with the simulations and the CNC machined pair have been inspected. Afterwards, the antennas are tested according to the MIL-STD-810H environmental condition test standard. It is concluded that all additively manufactured antennas are compatible with the results of the simulations. However, additively manufactured antennas failed in some environmental condition tests. Therefore, it is suggested that the fabricated antennas do not have satisfactory features to operate in military environmental

conditions.

Keywords: 3D printing, antenna fabrication, additive manufacturing, horn, military standard, environmental conditions



ÖZ

FARKLI EKLEMELİ İMALAT YÖNTEMLERİNİN BİR X-BAND HORN ANTENİ ÜRETİMİNDE KULLANIMI VE ÜRETİLEN ANTENLERİN MIL-STD-810H STANDARDI İLE UYUMLULUĞU

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3 Boyutlu Yazıcı teknolojisi oldukça hızlı gelişen ve birçok faydası bulunan katı imalat metotlarından. Bu teknoloji anten ve dalga kılavuzları için hızlı, ucuz ve hafif üretim yöntemleri sunmaktadır. Yapılan literatür taramasına göre FFF, SLA, Jetting, PBF gibi eklemeli imalat yöntemleri farklı frekanslarda çalışan anten tiplerinin üretiminde kullanılmış ve sağlıklı sonuçlar vermiştir. 3 Boyutlu Yazıcıların anten üretimindeki fizibilitesini test etmek için bir anten tipi belirlenmiş ve FFF, SLA ve Metal-FFF yazıcılar ile üretilmiştir. FFF ve SLA üretimi olan antenler bakır ile kaplanmıştır. Ardından üretilen antenlerin radyasyon parametreleri ölçülmüştür. Ölçüm sonuçlarının simülasyon sonuçları ve CNC üretimi antenin ölçüm sonuçları ile olan uyumlulukları incelenmiştir. Ardından antenler MIL-STD-810H askeri çevre koşulları test standardına göre testlere tabi tutulmuşlardır. Çalışmanın sonunda bütün antenlerin simülasyon sonuçlarına uygun olarak çalıştığı doğrulanmıştır. Ancak eklemeli imalat ile üretilen antenler çevre koşulları testlerinin bazılarında kalmışlardır. Bu sebeple üretilen antenlerin askeri çevre koşulları altında çalışmaya elverişli olmadığı anlaşılmıştır.

Anahtar Kelimeler: 3B üretim, anten üretimi, eklemeli imalat, horn, askeri standart, çevre koşulları





To my Family...

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LIST OF ABBREVIATIONS

ABBREVIATIONS

2D	2 Dimensional
3D	3 Dimensional
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
CAD	Computer-Aided Design
CNC	Computer Numerical Control
EM	Electromagnetic
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
IPA	Isopropyl Alcohol
PBF	Powder Bed Fusion
PLA	Polylactic Acid
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
STL	Standard Triangle Language

CHAPTER 1

INTRODUCTION

1.1 Motivation and Problem Definition

In this thesis, the suitability of additive manufacturing technologies on antenna fabrication will be analyzed with their advantages and disadvantages and a specific antenna model will be manufactured. Afterwards, the fabricated antenna will be tested according to the MIL-STD-810H environmental conditions test standard. Additionally, the radiation parameters of the manufactured antennas will be analyzed and compared with the other AM & CNC manufactured antennas. Therefore, the eligibility of AM technologies on antenna fabrication and the durability of these additively manufactured antennas under environmental stress conditions will be analyzed.

1.2 Proposed Methods and Models

In this thesis, the eligibility of AM technologies in the manufacturing of an antenna structure will be investigated by example fabrications with FFF and SLA methods. The fabricated models will be electroplated in order to obtain a radiating surface. Also, a fabrication with a novel Metal Fused Filament Fabrication (MFFF) method will be conducted. The fabricated antennas and CNC fabricated product will be compared in terms of manufacturing and mechanical properties. Afterwards, the antennas will be tested in terms of radio frequency quality. After the radio frequency measurements, the parts will be tested according to the MIL-STD-810H standard.

1.3 Contributions and Novelties

The contributions of this thesis are as follows.

- A horn antenna is manufactured via three different AM methods.
- A method to copper electroplate PLA and cured resin material is introduced.
- The geometric error encountered in the Metal-FFF method while sintering the antenna is minimized by performing several iterative productions.
- Radiative performances of the antennas fabricated via three different AM methods are analyzed and compared with the CNC manufactured antenna.
- Military environmental condition tests are employed on the additively manufactured antennas and the test results are discussed.

1.4 The Outline of the Thesis

In Chapter 2, background information is given and relative subjects for the study are explained. The studies that are comparable to the presented work are reviewed. In Chapter 3, the fabrication methods and post-process phases are explained in detail. At the end of this chapter, fabricated antennas are compared through several aspects. In Chapter 4, the radiative performance of the antennas with the military environmental test results are covered. In Chapter 5, the conclusions for the study are drawn.

CHAPTER 2

REVIEW OF THE STATE OF THE ART

2.1 Introduction

3D Printing (Additive Manufacturing) is a revolutionary solid manufacturing method that is capable of fabricating complex shapes with lower cost, lower weight and reduced time both in CAD/CAM and production phases without any mold or template necessity [2]. This straightforward, fast, cheap and easy-to-access technology democratized manufacturing and is used for rapid prototyping. Different 3D printing techniques are specialized for different types of materials, required resolution/tolerances, geometric limits and strength/flexibility properties.

These AM methods are summarized as follows. Fused Deposition Modeling (FFD) is the technology that uses the melt extrusion method where the filaments of thermal material deposited conforming to a specific pattern (Figure 2.1a). FFD is the most common method with a high range of suitable materials and decreased dimensional accuracy. In Stereolithography (SLA), ultraviolet (UV) laser is used as the energy source to cure polymer resin in the intended pattern (Figure 2.1b). The used material is liquid polymer resin and it provides excellent dimensional accuracy. Selective Laser Sintering (SLS) is the method that uses the laser to selectively sinter the particles of a convenient material in powder form, fuse them layer by layer and finally produce the intended geometry. The parts built by SLS have isotropic and desirable mechanical properties. Material Jetting and Binder Jetting are the jetting methods that 2D cures the base material with the help of UV light or spraying a binding agent layer by layer. Jetting methods are the most precise method currently and promise multi-color and full-color printing options [3]. In Powder Bed Fusion (PBF) pro-

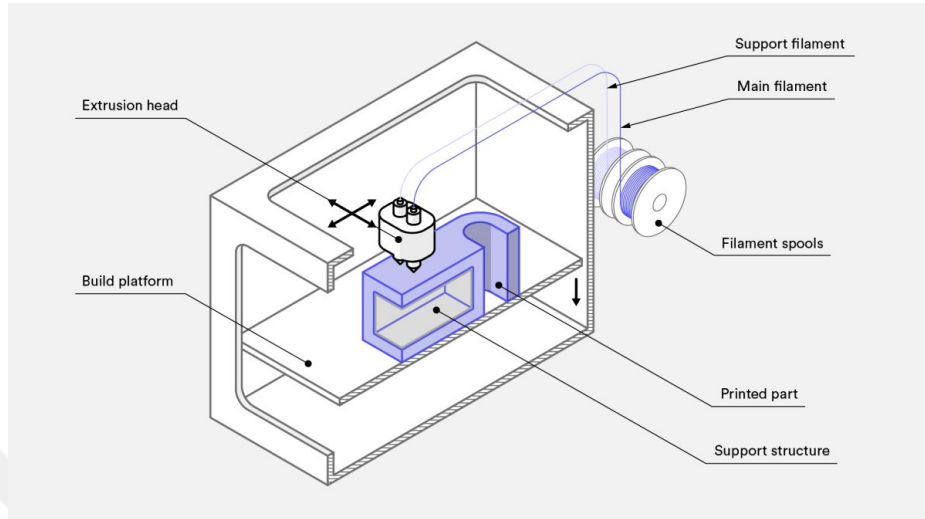
cesses the base material is powder and these powders are fused with the help of a laser, electrons or an adhesive material. This method promises products with superb mechanical properties with high dimensional accuracy.

So far, 3D printing is well-researched in sense of fabrication and mechanical properties while the application area is indefinite and promising [4]. With the ease of producing complex shapes in a fast and cheap manner, 3D printing became appealing for radio frequency and microwave implementations [4]. For electronic devices and antennas that require expensive/complicated manufacturing or a limited weight budget, 3D printing offers convenient solutions with operation bandwidth ranging from Medium Frequency to Extremely High Frequencies [4], [5]. Research has shown that 3D printed antennas can provide similar electromagnetic properties as antennas produced with conventional methods [6].

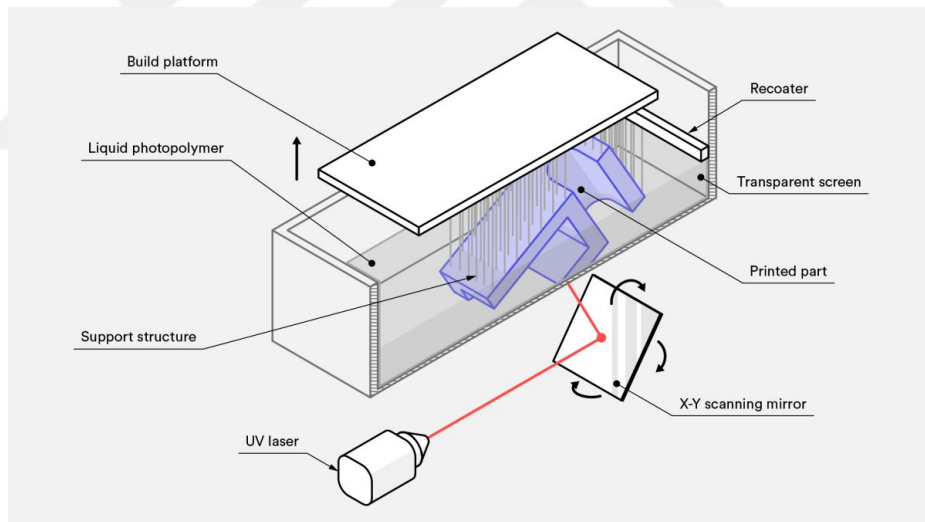
In this chapter, the antenna structures fabricated with AM methods have been investigated and this investigation will be analyzed in 5 subsections: FFF Applications, SLA Applications, Jetting and Powder Bed Fusion Applications, Other Applications & Effects of Parameters and Environmental Testing of the Additively Manufactured Antennas. These sections are further discussed as follows.

2.2 Fused Filament Fabrication Applications

Horn antennas are quite common in the high to extremely high (300 MHz - 150 GHz) frequency band. This type of antenna operate usually with directional radiation which leads to high gain and little loss [9]. Tak et al. [10] used FFF to produce an X-Band horn antenna bandwidth centered at 10 GHz with the assembling parts. The antenna was sprayed with conductive ink after the fabrication. In this research, the CNC machined antenna, 3D printed antenna and the simulation results were compared. Results showed that the 3D printed antenna is similar in terms of gain and reflection coefficient with the CNC machined pair and it is sufficient in terms of these parameters. It is worth mentioning that the 3D printed antenna was 215 grams while the CNC machined pair was 1112 grams which makes the FFF part 80% lighter. It is beneficial to denote that the weight difference is arising not directly from the fab-



(a) Fused Filament Fabrication [7]



(b) Stereolithography [8]

Figure 2.1: Schematics of FFF and SLA printing methods.

rication method but from the material used for the fabrication. Apart from Tak et al. [10], more research conducted on the subject. Toy et al. [6] and Chieh et al. [11] used FFF combined with a conductive metal coating approach to produce horn antennas as well. Toy et al. [6] has shown that the metal strip coated 3D printed pyramid horn antenna is sufficient for X-Band operations with the return loss attribute below -18 dB and the gain attribute over 12 dB, which conforms to the simulated results. Chieh et al. [11] produced a corrugated horn antenna operating in Ku - band with an FFF 3D printer and coated it three times with conductive ink. It is reported that the measured cross-polarization gain values were lower than expected. They expressed two probable causes for this; the conductivity of the coating material may be lower than the indicated value of the commercial product or the base material used for fabrication increases the dielectric loss. Helena et al. [12] manufactured 28 GHz centered pyramidal horn antennas via FFF to compare different filament types and plating types. It is reported that the antenna produced with metal filament has considerably higher bandwidth and gain values compared to the metal strip coated or spray-coated plastic antennas. In another study, Helena et. al. [13] mention that 3D printing quality for antennas ensures proper results for current and upcoming 5G/Internet of Things (IoT) scenarios. The accessible and economical solutions offered by 3D printing induce it as a viable manufacturing method. Castro et al. [14] fabricated a cylindrical horn antenna with PC-ABS material and two-layer coating via PSPI-1000 and PSPI-250 silver particles consisting conductive ink sprays sequentially. The research shows the CNC machined antenna and 3D printed antenna shows similar normalized radiation patterns with the simulation. It is denoted that 3D printed antenna's weight was 490 grams while the CNC machined aluminum antenna was 1578 grams which makes AM manufactured prototype 69% lighter. Genc et. al. [15] produced 2 by 1 and 2 by 2 horn array antenna structures by the FFF method and ABS material. After the fabrication, they electroplated the 3D printed parts and then assembled the structure. As reported by the study, it is possible to increase the gain parameter of the antenna by converting to an array antenna system and also AM quality is satisfactory for this fabrication. Macdonald et. al. [16] used a hybrid method to fabricate a patch antenna strengthened with isogrid reinforcement. This hybrid method involves FFF method improved with supplementary production capabilities of machining, wire integration, conductive foil placement, patterning and component placement. Macdonald et. al.

[16] states that with this hybrid, multi-process method it is possible to achieve structures with increased volumetric efficiency and potential weight savings.

2.3 Stereolithography Applications

Promising better resolution and accuracy, SLA is used in microwave applications as well. One of the earliest studies to fabricate an antenna with the SLA method is done by Huang et. al. [17]. They fabricated horn antennas working on Ku-band with SLA. After the fabrication, they applied a silver containing ink as a seed layer for further copper metallization. In the study, Huang et. al. [17] mentions SLA enables realizing complex geometries while preserving the radiation performance which is difficult to create using conventional fabrication techniques. Vorst et al. [18] manufactured a spline shaped horn antenna and a Ku-Band ring-focus dual-reflector antenna with SLA and coated it with copper and gold. Reduced mass and thermal insulation were the main advantages of 3D printing materials as specified in the research. They indicated that SLA fabrication quality is more than enough for Ka & Ku band (12 – 40 GHz) applications in terms of both co-polar and cross-polar radiation patterns and gain. To show implementations of SLA apart from horn antennas, Li et al. [19] produced a 5G MIMO antenna working on 3,5 – 5,1 GHz bandwidth with the SLA method. The measurement results specify that the SLA method is adequate for current telecommunication technologies. Also, they warned that high power applications can be a problem for resin material. Thus, a thermal analysis may be required in high temperature applications. Array antennas are another application area for the SLA process. Le Sage et al. [20] produced a customized high gain 2 by 2 array antenna under \$1K in a few weeks, which costs \$10K and 6 months of delivery period if purchased from the commercial suppliers as indicated in the paper. They reached 30 dB gain at 21 GHz with 95% antenna efficiency which is approximately identical to the aluminum pair. Their work features as the first high-gain array antenna manufactured via 3D printing. Mirmozafari et. al. [21] used SLA technology to produce a linear array antenna. In the study, it is reported that a conveniently low active reflection coefficient and a sufficient cross-polarization intensity were reached. Su et. al. [22] produced flexible origami antenna trees with the UV curing SLA method. They used

Formlabs flexible resin (FLGR02) with 80% elongation property in their production. They also used a Voronoi structure in their product to support the helical and zigzag antenna structure with the least mass amount possible. After the fabrication, they used a liquid metal alloy namely EGaIn which has radiative and elongation properties. This alloy performs a never-fail bending nature and continuously heals itself when a crack occurs. The measurements showed that the fabricated antennas have similar radiation parameters as the simulations.

2.4 Jetting and Powder Bed Fusion Applications

Jetting and Powder Bed Fusion (PBF) processes are other AM methods and are adequate to manufacture antennas. For applications on an antenna working on higher bandwidth, Nayeri et al. [23] used a Material Jetting (MJ) 3D printer with 16 μm slicing thickness. Three prototypes were designed with an operating bandwidth of 0,1 THz. Gain values at 0,1 THz were about 20 – 22 dB with radiation efficiencies up to 80% coherent with the simulations done via Ansys HFSS. A typical study was done by Zhang et al. [4]. They used Binder Jetting (BJ) technology to manufacture a metallic 3D printed antenna working on EHF (Extremely High Frequency) to sub-millimeter (Terahertz) bandwidth. Two different metal powders were used for fabrications, Cu15Sn and 316L. Due to lower surface roughness, Cu-15Sn antenna has been selected for further investigation. Fabricated antennas were functional on all three bandwidths with 0,5 – 1 dB gain discrepancy with the simulated results. According to the research, surface roughness is the main cause of the loss in the sub-millimeter bandwidth. Zhang et al. [24] also manufactured a conical horn antenna using the Selective Laser Melting (SLM) technique and Cu-15Sn powder in another research which operates between 60 – 90 GHz frequency band. The antenna gives convenient results with the simulation results in terms of gain and normalized radiation patterns. In the research, they mentioned that the SLM manufactured waveguides and radio front-end operate consistently with the simulations. In the study, Zhang et al. [24] used an ultrasonic sink to shake off the leftover Cu-15Sn powder and manual polishing to decrease overall surface roughness. Gu et al. [25] used MJ and metal BJ to produce a resonant cavity antenna operating at 30 GHz. They introduced a

two-step procedure for copper plating the polymeric antennas, painting the antenna with a silver containing ink and then immersing the antenna into a copper sulfate tank for 5 minutes in the presence of a DC power supply. The results were in agreement with the simulations, which confirms AM as a viable option for a robust antenna design. Shin et. al. [26] manufactured a Ku-band steerable phased-array antenna subsystem by both using polymer jetting and fused filament fabrication. They reported that this low-cost antenna subsystem has excellent radiation properties. This study demonstrates that different additive manufacturing technologies can be utilized simultaneously while producing an assembly formed by several parts.

2.5 Other Applications & Effects of Fabrication Parameters

In the comparison of different AM technologies, Peverini et al. [27] produced two different waveguides operating on Ku - K band frequencies. For the first design, they manufactured 4 different prototypes; SLA using ABS-like polymer, SLM using AlSi10Mg, SLM using Ti6Al4V and SLM using steel. SLA fabricated waveguide was the lightest one and the most precise in terms of dimensional accuracy. While the aluminum based antenna was the most conformable with the simulation results, the other prototypes were moderate. It is beneficial to point out that SLA fabricated waveguide had poor performance in terms of insertion loss. In the second design, the methods and the materials were the same. Again, the aluminum antenna had the best properties and other SLM printed antennas were moderate, the SLA fabricated antenna did not give acceptable results. The cause of this situation was the improper copper coating of the inner features of the SLA fabricated antenna as pointed out by Peverini et al. [27]. In another study, Helena et. al. [28] fabricated two horn antennas operating on Ku-band: The first one is printed with PLA material and then covered with copper tape and the second one was printed directly with conductive PLA. While the first prototype was more favorable in terms of simulated efficiency, the second one provided approximately 65% broader bandwidth.

Ghazali et al. [29] used 3D printing technology to highly customize the printed antennas. In his work, he produced patch shaped, 's' letter shaped, 'e' letter shaped, Spartan logo shaped and Bilateral Vivaldi antennas with material jetting. Even though

the efficiencies of these antennas were low (except for Bilateral Vivaldi), the research demonstrates the ease of design customization with 3D printing.

Rabinskii et al. [30] produced a transceiver housing plate with built-in liquid cooling channels using SLM technology and AlSi10Mg powder. The mechanical properties of the transceiver were similar to those obtained by traditional manufacturing methods. Gjokaj et al. [31] used a hybrid additive manufacturing method to produce an active receive circuit embedded Vivaldi antenna. With the design, a high functional density system and improved receive power were obtained. These studies propound the possibility of manufacturing antennas with built-in functions such as cooling, sensors, wiring, etc. , which lead to faster and more complete manufacturing with fewer assembling parts.

Aside from the fabrication of antennas, some research was concentrated on how fabrication parameters affect antenna efficiency. Garcia et al. [32] and Honari et. al. [33] investigated the effects of surface roughness on efficiency. While they both agree that increasing the surface roughness can cause a decrease in the performance of the antenna, Garcia [32] states that it does not have a measurable effect on the antenna efficiency up to a certain degree. This drop becomes dramatic in higher bandwidth applications as reported by Zhang et al. [4].

Coating of the 3D printed antennas is another subject for consideration. Yao et al. [34] investigated the difference between paint-coated and tape-coated antennas. Results show that the paint-coated antenna was far more favorable despite having decreased conductivity on its surface. Thus, in further investigations, it is beneficial to avoid using strip metal coatings. Chuma et al. [35] produced X-Band horn antennas via FFF method and covered the antennas with copper plating, copper tape and silver paint. In terms of gain and radiation pattern, the results of copper plating were closest to the simulations. From the research, it can be seen that the copper plated antenna was the most favorable one while the copper tape covered antenna was moderate and silver painted antenna has the poorest quality in terms of the gain parameter.

2.6 Environmental Testing of the Additively Manufactured Antennas

While the radiation quality is adequate for radio frequency applications, the durability of the additively manufactured antennas during challenging environmental conditions is another subject for consideration. Enakerakpo et. al. [36] manufactured a dipole antenna resonating at 2,41 GHz and 4,63 GHz. They produced antennas with and without coating and then tested these antennas according to the MIL-STD-810 standard. Among the test methods, high and low temperature tests, thermal shock test, temperature and humidity test and water immersion tests are applied since they are considered as relevant to the life cycle of the antennas. It is seen that all antennas are robust in these test conditions.

Dimitriadis et. al. [37] produced a 2 by 2 array horn antenna with the SLA method and then coated the antennas with an electroless copper plating technique. They tested the antennas with a standard scotch tape test according to the ASTM Standard D3359-09. Then, thermal cycling between extreme temperatures (-55°C to 75°C) for airborne standard EUROCAE EDB14G is applied. It is recorded that the polymer material with the electroless plating procedure manages to pass these environmental tests without any observable degradation. In another study, Gill et. al. [38] produced an antenna feed array with Direct Metal Laser Sintering (DMLS) method and investigated the spaceworthiness of the fabricated product. Hardness test, thermal conductivity test and tensile test are applied to the material and it is reported that the material properties are convenient. Apart from the material properties; thermal cycling test, thermo-vacuum test and vibration test are conducted on the part. No degradation is observed under these tests either.

Kyovtorov et. al. [39] fabricated a horn antenna working on 14-18 GHz with ABS material via FFF. Three samples are manufactured diversifying by the coating method: chemical deposition, electrochemical deposition and with two of the methods combined (two layers of copper). The coatings are tested according to the Tape-Test-Method ASTM-D 3359-83. After the tape test, which was successful, the uniformity of the coatings are analyzed with X-ray fluorescent analysis. This non-destructive analysis verified the adequate quality of the metal layers. Additionally, the antennas provided more than 95% similarity in the radio frequency tests with the simulations.

Neff et. al. [40] tested the resiliency of two different conductive inks printed on the polyether ether ketone (PEEK) substrate. The environmental test is conducted according to the MIL-STD-331C standard. The environmental testing includes exposure to high accelerations and exposure to thermal cycling from -54° to 71° . While one of the inks is not degraded with any of the environmental tests, the other one is affected severely due to exposure to high accelerations. In the study, RF test results confirm this inference. He et. al. [41] produced RFID tag antennas with the direct deposition method onto a copper pad. The material used in printing is graphene which is an environmentally friendly and low-cost conductive material. In the study, He et. al. [41] tested the effects of high humidity on the RF performance of RFID tags. The results show that the performance is degraded shortly after exposure to a high humidity condition but as time went by, the effects are diminished. After a period of one week, the effects become negligible.

2.7 Closure

Considering the research conducted in the related field, AM is a viable option for antenna fabrication. FFF with the conductive coating is generally a cheap and an easy-access solution with moderate quality of dimensional accuracy and radiation. SLA with the conductive coating is excellent in terms of dimensional accuracy, but the difficulty of the proper coating of the inner features and sensitivity to the high temperature must be taken into consideration. PBF and MJ methods are suitable for high-frequency operations and give excellent radiation properties. Keeping in mind the literature survey done on the additively manufactured antennas, example fabrications and measurements are done in the following chapters.

CHAPTER 3

ADDITIVE MANUFACTURING OF THE HORN ANTENNAS

A pyramid horn antenna (Pasternack PE9856/SF-10 Model) working on X-Band (8-12 GHz) is selected as the example design and is fabricated by AM methods. In this chapter, the manufacturing processes of the selected antenna are explained in detail. The chapter is divided into three parts: *FFF and SLA Fabrication*, *Metal-FFF Fabrication* and *Comparison of the Fabricated Antennas*. The division of the fabrication section is due to the design and post-processing variations between the methods.

3.1 FFF and SLA Fabrication

The solid geometry for the horn antenna is designed on the Siemens NX11 Computer-Aided Design (CAD) software. The dimensions are obtained from the technical documents of the Pasternack PE9856/SF-10 model X-Band horn antenna which was available online [42]. The commercial product can be seen in Figure 3.1a and the designed 3D model can be seen in Figure 3.1b. Technical drawings of the designed antenna and the Pasternack PE9856/SF-10 are provided in Appendix A.

Before finalizing the design phase, it is beneficial to consider the skin depth effect which is an essential parameter for the radiating surfaces. The skin depth is the distance below the conducting surface where the current density has reduced to $1/e$ or 36,8% of its surface value. The skin depth of a conductive surface is calculated by the following equation

$$\delta = 1/\sqrt{\pi f \mu \sigma} \quad (3.1)$$

where δ denotes the skin depth, f is the frequency, μ is permeability constant ($4\pi \times 10^{-7} H/m$) and σ is the conductivity.

In the calculation, the frequency is selected as the center of the working bandwidth which is 10 GHz. Material for the radiating surface is selected as copper due to its high conductivity and lower expense and availability. The required skin depth at 10 GHz is found as 0,652 μm for copper. For proper radiation, suggested radiating surface thickness is recommended as at least 3-4 times larger than the skin depth which concludes to 2,5 μm . Since the skin depth value is insignificant considering the fabrication tolerances, this effect on the CAD model is ignored.

For the coating purposes, explained in detail later in this chapter, a little circular bump is added to the top of the base section of the antennas in the FFF and SLA designs. This bump is the place where electrical conductivity between the dc power supply and the antenna occurs and therefore is the starting point of the electrically induced coating process. This bump is not a radiating surface. Hence, the surface quality of this area is insignificant.

The radiation pattern and the return losses of the designed antenna, which are the most substantial measures used in order to compare the manufactured antennas' ra-

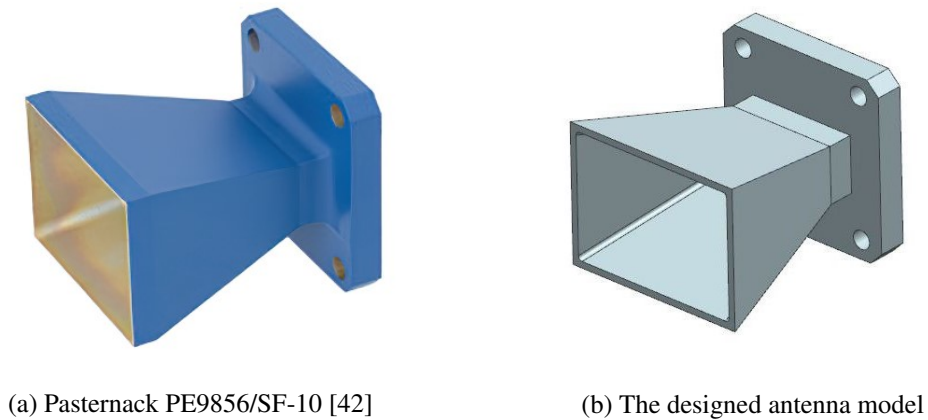


Figure 3.1: Selected antenna

diation performance are simulated via CST Studio afterwards. After finalizing the simulations, the model is exported as an *.stl* file for fabrication purposes.

3.1.1 FFF Fabrication

For the FFF fabrication, Ultimaker 3 Extended 3D printer is used. The build material is selected as PLA. Slice thickness is set as $100\mu\text{m}$. Support structures are not needed since there are no overhang surfaces exceeding 45° . The 3D printed antenna can be seen in Figure 3.2. Brim is used as the build plate adhesion method to make sure that the part is properly manufactured. Fabrication parameters are listed in Table 3.1.

Table 3.1: Fabrication parameters for the FFF method.

Material	PLA
Workpiece Size (mm)	50,8 x 43,2 x 48,9
Filament Diameter (mm)	2,85
Layer Thickness (μm)	100
Nozzle Diameter (mm)	0,4
Number of Shells	3
Infill Density (%)	100
Build Plate Adhesion	Brim
Travel Speed (mm/s)	70
Build Time (min.)	338

3.1.2 SLA Fabrication

For SLA fabrication, Formlabs Form 2 3D printer is used. The build material is selected as Clear Resin. Slice thickness is set as $50\mu\text{m}$. Support structures are not needed since there isn't any overhang angle exceeding 45° .

To have an appealing surface clarified from any sticky, excess resin material, the printed parts must be washed. For this purpose Formlab's Form Wash is used. Iso-

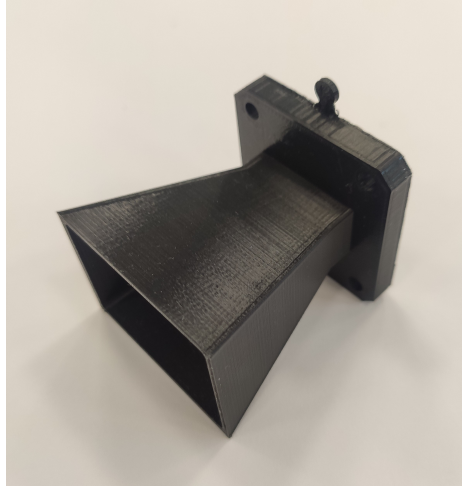


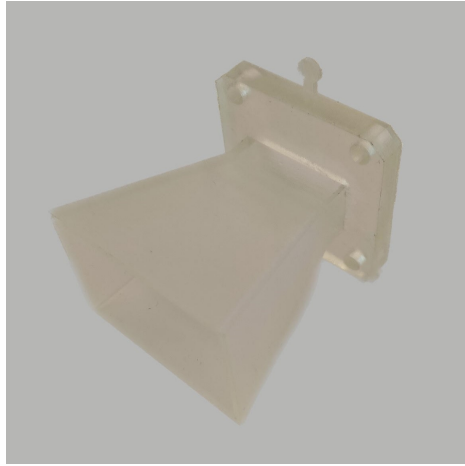
Figure 3.2: FFF printed antenna

propyl Alcohol (IPA) is used for washing. After the washing process, additional curing must be performed for polymerization reactions to be completed and final material properties to be obtained. Form Cure is used for this purpose. In the device, UV light is used for curing the resin material.

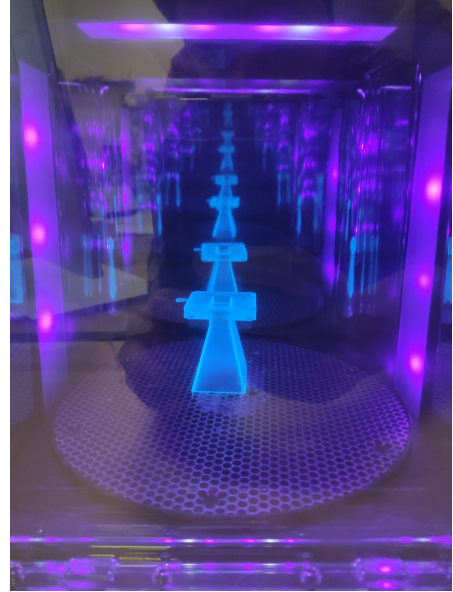
Fabrication parameters for the SLA fabrication are listed in Table 3.2. The fabricated part can be seen in Figure 3.3a. The curing phase can be seen in Figure 3.3b.

Table 3.2: The build parameters for the SLA fabrication.

Material	Clear Resin
Layer Thickness (μm)	50
Laser Power (mW)	250
Build Time (min.)	345
Washing Time (min.)	10
Curing Time (min.)	30
Curing Temperature ($^{\circ}\text{C}$)	60



(a) SLA printed antenna



(b) Ultraviolet curing of the antenna

Figure 3.3: SLA fabrication of the antenna

3.1.3 Copper Electroplating of FFF and SLA Fabricated Antennas

To broadcast in radio frequencies, the radiating surfaces must be conductive. Since PLA and Clear Resin materials are not conductive by their nature, it is obligatory to apply a post-processing method to cover the fabricated antennas with conductive materials. The cover material for the radiating surfaces is selected as copper due to its high conductivity, availability and lower cost. Electroplating is selected as the metallization method.

Electroplating is the broad term for the processes where a solid substrate is metal-coated with the help of an electrical current. The high purity of the plated metal and its sensitive coating ability of narrow spaces make electroplating a convenient choice for the covering process. Generally, electroplating processes are applied if a solid substrate is wanted to equip following qualities.

- Increased wear resistance
- Protection against surface abrasions

- Reduced friction
- Improved electrical conductivity

Electroplating is performed in a special ambient called an electrolytic cell. Chemical reactions are utilized with the help of the electrical energy in the electrolytic cell. The system consists of a DC power supply, electrolytic solution and electrodes. The electron donor electrode is called anode while the electron acceptor electrode is the cathode. Therefore, oxidation reactions occur at the anode and reduction reactions occur at the cathode. The anode must be positively charged while the cathode must be negatively charged. The metal material used for the plating must be connected to the anode (positive terminal). The substrate that will be plated must be connected to the cathode (negative terminal). The electrolytic solution must be prepared with a salt of the metal material used for plating. In our case, the plating material is copper and the substrate is additively manufactured antennas in the previous sections. The salt of the copper is copper sulfate ($CuSO_4$). The general schema of the process can be seen in Figure 3.4.

Before applying the electroplating process, it is substantial to know that both electrodes must be electrically conductive to induce reduction and oxidation reactions driven by electricity. The anode is copper material which is highly conductive but the cathode substrates are PLA and cured resin. These materials are plastic and therefore not conductive. Accordingly, these antennas should be coated with a semi-conductive material as a binding agent between the copper atoms and PLA or Clear Resin. Adhesive graphite spray is a satisfactory solution to initiate electroplating [43]. Kontakt Chemie's Graphite 33 Spray is chosen for pre-coating the antennas before the electroplating process. The graphite spray and coated antennas can be seen in Figure 3.5.

After the electrolytic bath and graphite-coated antennas are ready, the electroplating process is started. The voltage is kept at 0,15 Volts. The electroplating setup can be seen in Figure 3.7.

The optimum amount of voltage is determined by the trial and error method. Previous trials were 8 Volts, 2 Volts and 0,5 Volts. The samples can be seen in Figure 3.8. These

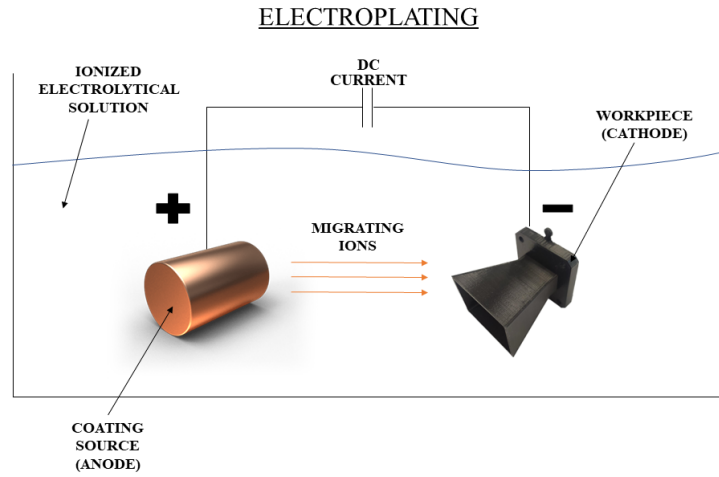
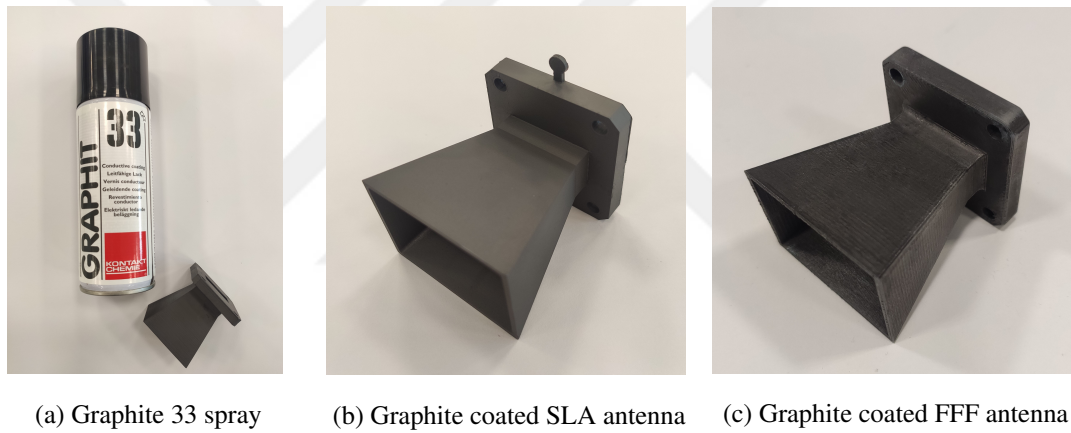


Figure 3.4: Schema of the electrolytic cell



(a) Graphite 33 spray

(b) Graphite coated SLA antenna

(c) Graphite coated FFF antenna

Figure 3.5: Graphite 33 spray and pre-coated antennas

voltage values are higher than nominal for the geometry and cause either the graphite powder to burn and not electroplate the area or electroplating rapidly and pile up the copper on certain areas and therefore alter the surface quality.

As mentioned earlier, for coating purposes, a little circular bump is added to the top of the base section of the antennas in the FFF and SLA designs. This bump is the place where electrical conductivity occurs and therefore is the starting point of the electrically induced coating process. It is realized that after the electroplating process is finished, electrical connection becomes uneven and substandard in terms

Table 3.3: The chemicals and their quantities used for the electrolytic solution.

Chemical	Used Amount	Percentage
Distilled Water	2000 ml	79,4%
Copper Sulfate	500 ml	19,85%
Sulfuric Acid	17 ml	0,67%
Polyethylene Glycol	1,7 ml	0,067%



Figure 3.6: Electrolytic solution

of coating. The bump is used for electrical connection between the DC power supply and the antenna and its surface has low coating quality.

As seen from the trials, it is concluded that the lower voltage results in higher quality surfaces but as the voltage decreases, the amount of time necessary for electroplating increases. The trial with 0,15 Volts produced a fine-quality copper surface on the antenna geometry within an acceptable period of time. The process took 10-12 hours in total for 1 antenna. The progress can be seen in Figure 3.9. It shows the timelapse of the electroplating process. Pictures were taken every 2 hours during the plating process.

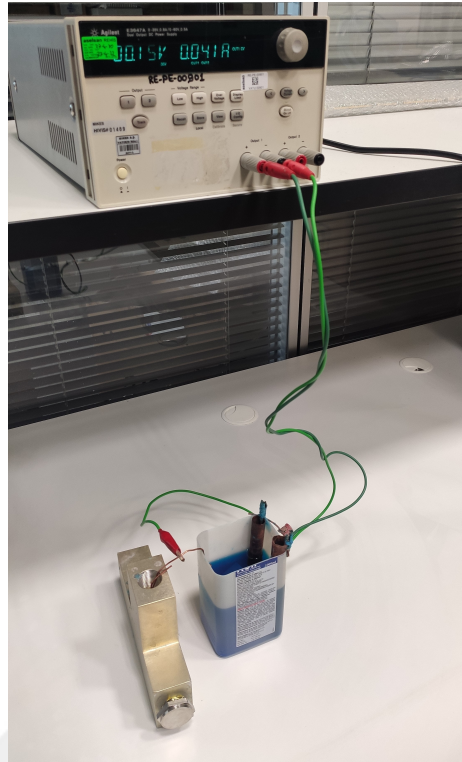


Figure 3.7: Electroplating setup

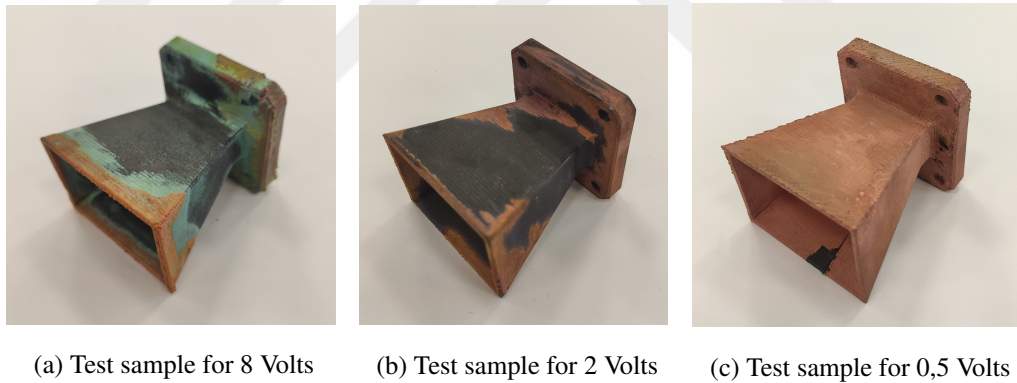


Figure 3.8: Unsuccessful electroplating trials

Before finalizing the fabrication process, it is essential to measure the coating thickness in order to make sure that a decent amount of skin depth is achieved, which is $2,5 \mu\text{m}$. For the measurement, Fischerscope X-Ray Analyzer is used. The average coating thickness is calculated as $16,9 \mu\text{m}$ for the FFF antenna and $21,4 \mu\text{m}$ for the SLA antenna. The results are considerably higher than the required skin depth value. Therefore, it is concluded that the coating thickness values are adequate. The

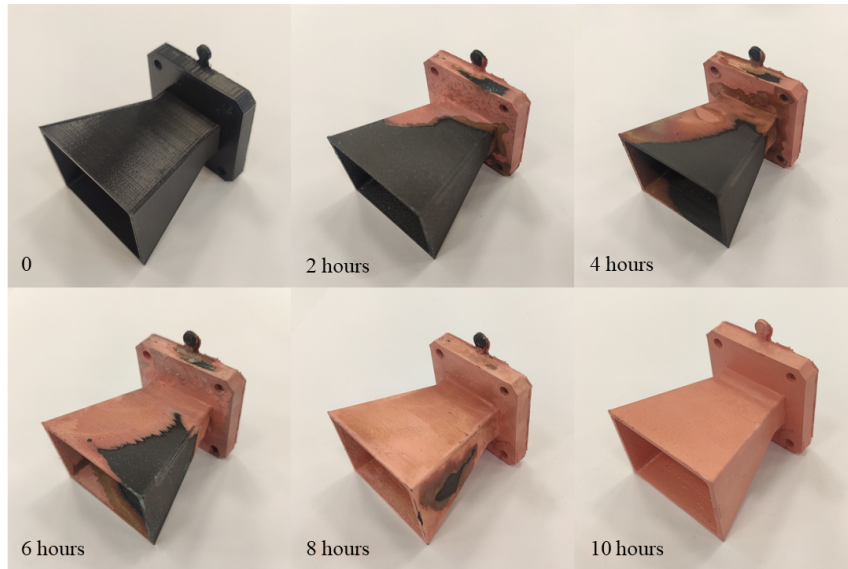


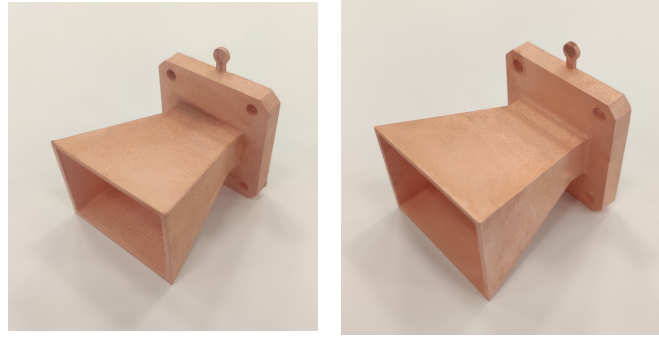
Figure 3.9: Timelapse of the electroplating process

measurement process can be seen in Figure 3.10.



Figure 3.10: X-Ray measurement of the coating thickness

After the electroplating process is completed, the SLA and FFF fabricated antennas are ready for measurements and tests that are discussed in the next chapter. The finalized FFF and SLA antennas can be seen in Figure 3.11.



(a) FFF antenna

(b) SLA antenna

Figure 3.11: Electroplated antennas

3.2 Metal-FFF Fabrication

Metal-FFF is used to print metal parts by the filament extrusion method. It is a modified version of the FFF suitable for printing metal parts via materials in the form of filaments. For the Metal-FFF fabrication, Markforged's desktop-sized Metal-X printer which makes use of ADAM Metal Printing technology is used.

This technology is quite similar to the FFF method and is a material extrusion technique where a filament material is extruded through a heated nozzle and joined together layer by layer to fabricate solid parts. This special filament is composed of metal powder and binding agents. These binding agents are used for shaping the metal powder content of the filament while printing the object. At this moment, the printed object is called the green part. After printing, some of these binding agents are dissolved in the solvent wash stage. For this stage, another device specialized for the washing of the green parts is used. And finally, to fuse the metal powders, a special furnace is utilized. This stage is called as sintering. The metal powders are fused into solid metal in this stage.

Markforged's Metal X model 3D printer has a build volume of $250mm \times 220mm \times 200mm$ and a $575mm \times 467mm \times 1120mm$ footprint. The washing station is named as WASH-1. The company offers sintering furnaces in two different sizes: SINTER-1 as the medium size and SINTER-2 as the larger one. The printer, washing station and furnace are complementary devices that are designed for the same standards and used

for the Metal-FFF fabrications in this thesis. The 3D printer can currently print the following materials:

- 17-4 Stainless Steel
- 303 Stainless Steel
- 6061 Aluminum (Beta)
- 7075 Aluminum (Beta)
- A-2 Tool Steel (Beta)
- D-2 Tool Steel (Beta)
- IN Alloy (Inconel) 625 (Beta)
- Titanium Ti-6Al-4V (Beta)
- Copper (Beta)

For the fabrication of the antenna, copper material is chosen due to its high conductivity. Disregarding the complexity and immaturity of the technology, the first naive attempt was to print the same geometry used for the FFF and SLA fabrications. The first error in fabrication is encountered in the green part stage. After successfully printing the object, the part broke down due to a slight collusion during the transfer from the printer to the solvent wash. This accident showed how fragile the green part is and how careful should the authorized personnel behave between the stages. The wreck of the printed object after the accident can be seen in Figure 3.12.

After the incident, the same model is printed and successfully washed and sintered. But unfortunately, it is realized that during the sintering operation the thin walls of the antenna lean outwards due to high temperature. At the temperature of 1300°C, the walls are not able to carry their own weight and therefore the dimensional accuracy could not be maintained due to bulging. The printed and sintered part can be seen in Figure 3.13.



Figure 3.12: The fractured green part



Figure 3.13: First trial of the Metal-FFF method (MFFF-1)

To eliminate the bulging on the thin walls, the design updated. As support structures, columns are added to the CAD model. Also, a different copper filament is used in order to see if the error is material related. Assuming these improvements would eliminate the error, the printing process has started again. The CAD model and the printed object can be seen in Figure 3.14.

Unfortunately, these precautions did not solve the problem completely but the amount of displacement on the walls has reduced drastically. The improvement can easily be seen in Figure 3.16. The leftmost figure is the first trial, while the middle one is the second and the rightmost is the final version. The technical drawing of the designed model is provided in Appendix A.

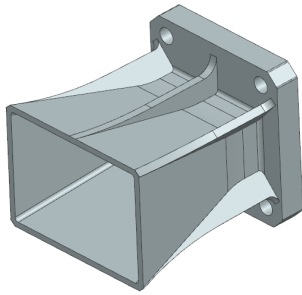


Figure 3.14: Second trial of the Metal-FFF method (MFFF-2)

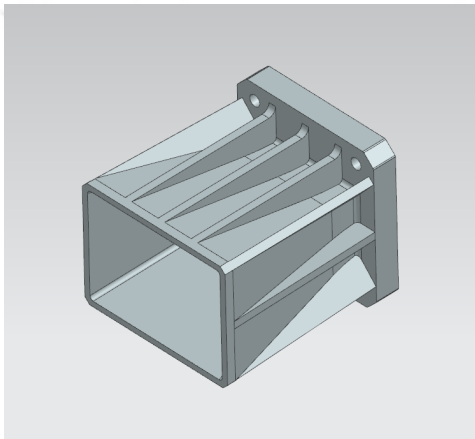


Figure 3.15: The final trial of the Metal-FFF method (MFFF-3)



Figure 3.16: Top view of the Metal-FFF fabrications

3.3 Comparison of the Fabricated Antennas

After the antenna fabrications are completed, it is beneficial to compare them in terms of dimensional accuracy, cost, coating thickness, surface roughness, weight and mechanical properties with fabrication time.

To compare the antennas in terms of dimensional accuracy, a technical drawing of the antenna is prepared. In this drawing, 5 essential dimensions that affect the radiation are defined and labeled. Then CMM measurements of the fabricated antennas are performed. The measurement process can be seen in Figure 3.17. The measurements with the amount of error in percentage are tabulated. The critical measurement locations can be seen in Figure 3.18, and the table for dimensional accuracy can be seen in Table 3.4. As seen from the table, MFFF-3 is the best antenna among the MFFF fabrications in terms of dimensional accuracy. Therefore, MFFF-3 will be used in the further comparison between the fabrication methods and tests which will be explained in the following chapter. Notice that the Pasternack PE9856/SF-10 is denoted as the CNC manufactured antenna in the comparison tables. Also, notice that the CNC manufactured antenna is the best one among the antennas in terms of dimensional accuracy. SLA antenna comes in second and noticeably, it has one of the critical dimensions more accurate than the CNC antenna. Worth mentioning, the SLA antenna may be more successful than CNC fabrication with a higher resolution setting. The FFF antenna is the third most successful antenna with moderate accuracy. MFFF antennas are the lowest accurate antennas. The reason for this situation is the sagging behavior of the material in the sintering stage. This behavior causes the part to have vast dimensional errors and the results don't reflect the general accuracy of the printing system but the design struggles of the MFFF process.

The second aspect for comparison is the cost. For printing the objects, the prices are reported by the local manufacturers as \$13 for FFF, \$57 for SLA and \$440 for Metal-FFF. Metal-FFF antenna does not require a post-processing since it is made out of copper. Therefore \$440 is the total cost of the Metal-FFF fabricated antenna. Graphite 33 spray is \$15 and is capable of successfully coating 10 antennas in one pack, so it costs \$1,5 for graphite coating of one antenna. For the electroplating mixture, two liters of distilled water costs \$3, 500 *ml* of copper sulfate is \$4, 17 *ml* of sulfuric acid

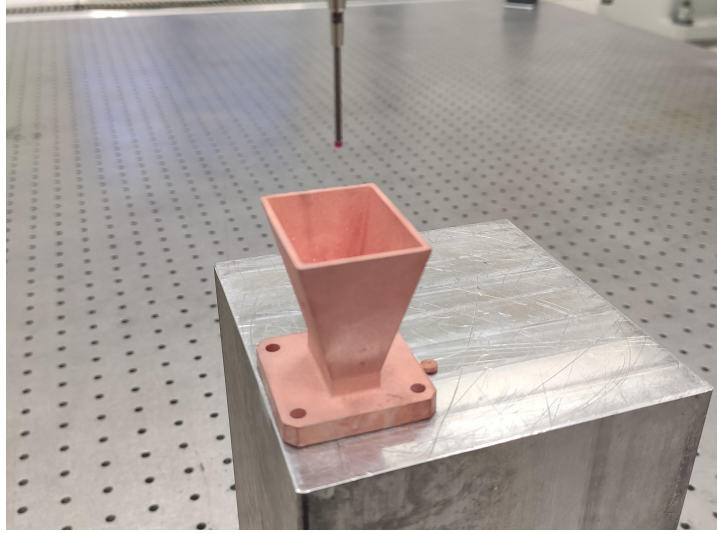


Figure 3.17: CMM measurement of the antennas

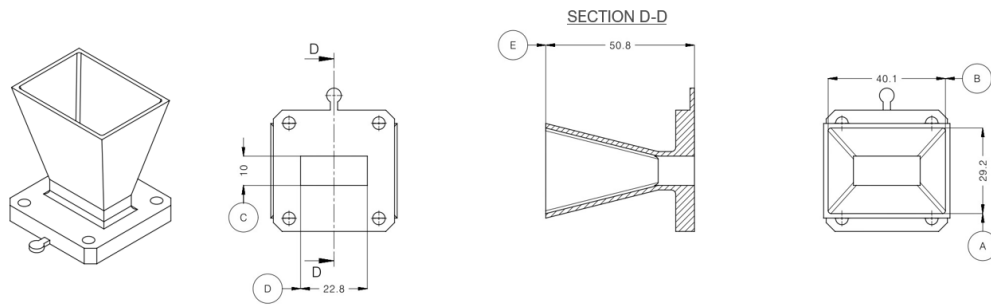


Figure 3.18: Critical dimensions of the horn antenna

is \$0,5 and 1,7 *ml* of polyethylene glycol is \$0,5. The pure copper rod of 25 *gr* is \$6. The total cost for a two-liter mixture with the copper rod is \$14 and this mixture is sufficient enough to electroplate 10 antennas. So, the material cost for electroplating per antenna is \$2,9. As of November 2022, the hourly minimum wage in Turkey is \$2. Since the process is carried out by a skilled worker, it is fair to take hourly labor cost as \$3. Considering one antenna will take about 2 hours of the worker's time, the total labor cost per antenna is \$6. So, electroplating an antenna without any profit costs \$8,9. With a fair profit margin of 30%, the price for copper electroplating per antenna is \$11,6. The antenna model is sent to the local manufacturers for CNC

Table 3.4: The CMM measurements of the antennas with the amount of error percentage.

Method	29,2 mm	40,1 mm	10 mm	22,8 mm	50,8 mm	Avg. Error
FFF	29,22	39,65	9,72	22,52	51	1,12%
	+0,06%	-1,12%	-2,8%	-1,23%	+0,4%	
SLA	29,21	39,96	9,82	22,57	50,53	0,74%
	+0,03%	-0,35%	-1,8%	-1%	-0,5%	
MFFF-1	34	37,41	9,43	22,42	50,95	6,15%
	+16,4%	-6,7%	-5,7%	-1,66%	+0,3%	
MFFF-2	32,69	38,77	9,86	22,96	52,03	3,94%
	+11,9%	-3,3%	-1,4%	+0,7%	+2,4%	
MFFF-3	30,71	39,95	10	22,89	51,52	1,47%
	+5,17%	-0,37%	+0%	+0,4%	+1,42%	
CNC	28,97	39,98	10,12	22,85	50,88	0,53%
	-0,79%	-0,3%	+1,2%	+0,22%	+0,16%	

manufacturing cost analysis. The average price excluding the coating was \$177. The chromate coating costs \$5, which is \$182 in total. Consequently, the total prices of antennas are the following: \$24,6 for FFF, \$68,6 for SLA, \$440 for Metal-FFF and \$182 for CNC machining. The FFF antenna is the cheapest one as expected due to the availability & low cost of the 3D printer and filament material. SLA fabrication is the second cheapest one and CNC machining is the third. Metal-FFF is the most expensive one with a significant price difference. It is more than the double price of the second most expensive antenna. This is majorly due to the technology being novel and neither the printer nor the filament material being easily accessible.

The surface roughness values of the antennas are measured via the surface profilometry method. For each antenna, 4 measurements are performed from 4 different radiating surfaces. It is reported that the average surface roughness (Ra) of the radiating surfaces is 7,79 μm for FFF, 5,32 μm for SLA and 9,99 μm for Metal-FFF. For CNC manufactured antenna the roughness average is 1,32 μm which is substantially lower

than the additively manufactured antennas. Lower surface roughness may be one of the substantial factors for better radiation quality. The best one in terms of surface quality is the CNC antenna. The second is SLA and the third one is FFF. The lowest surface quality is achieved in the MFFF antenna. Notice that the results are parallel to the dimensional accuracy results. Thus, it can be argued that there is a correlation between dimensional accuracy and surface roughness.

Mechanical properties of the parts are not measured but obtained from online datasheets [44], [45], [46], [47]. Density, tensile strength, tensile elongation and melting temperature values are compared. The data can be seen in Table 3.6. As seen from the table, the metal antennas are more favorable in terms of mechanical strength and endurance. The plastic antennas are more brittle and have lower strength values as expected.

Another parameter for consideration is the weight of the antennas. The FFF fabricated antenna is 18,2 *gr* while the SLA antenna is 20,7 *gr*, the M-FFF antenna is 243 *gr* and lastly, the CNC antenna is 43,5 *gr*. The plastic antennas are considerably lighter than the metal antennas. The CNC antenna has a moderate weight but the MFFF antenna has an enormous weight compared to the others. This happens due to copper being a dense metal and the necessity to add support structures to the design in order to minimize sagging during sintering process.

Lastly, fabrication time for each antenna is elaborated. The printing time for FFF is 6,5 hours. The electroplating takes 10 hours for one antenna. Thus, the total fabrication time for FFF is 16,5 hours. The printing time for the SLA 3D printer is 4 hours. Afterwards, 2 hours of UV curing is applied to the parts. With the electroplating, the total required time for SLA fabrication is 16 hours. For the Metal-FFF method, printing the part takes 24 hours, washing takes 22 hours and sintering takes 29 hours. The total fabrication time for Metal-FFF is 75 hours. For the CNC manufactured antenna, the local manufacturer reported that it takes 24 hours to obtain the raw material which will be processed and 4 hours for the CNC operations. It makes 28 hours in total. The results are confirming that AM is suitable for rapid prototyping. Only the MFFF method takes more time than CNC machining since it is a three-stage fabrication including washing and sintering. These processes are not required in the other methods.

After the fabrication parameters are obtained, an importance value for each property is determined. Since the efficiency of the antennas is affected significantly by the surface roughness the most crucial property is selected as the surface roughness with 0,25 relative importance. The second most important aspects are selected as cost and average dimensional error with 0,2 importance. It is beneficial to denote that the antenna radiation characteristics can alter due to dimensional errors. Fabrication time is selected as the fourth important property with 0,15 relative importance. Weight, strength, elongation and melting temperature are selected as the least important aspects with 0,05 relative importance since they have no direct effect on the fabrication or the efficiency of the antennas. Afterwards, a lower and a higher bound is set for each property. These are the values that will be used to obtain the ratio value of each antenna property read between 0 and 1 for further rating computation. Preference of each merit is determined as high or low. With these criteria Table 3.5 is prepared. The results of this rating can be seen in Table 3.6.

Table 3.5: Rating criteria of the antennas.

Property	Rel. Imp.	Units	Low	High	Pref.
Dimensional Error	0,2	%	0,5	1,5	Low
Cost	0,2	\$	0	500	Low
Surface Roughness	0,25	µm	0	12	Low
Weight	0,05	gr	0	250	Low
Tensile Strength	0,05	MPa	50	350	High
Tensile Elongation	0,05	%	5	30	High
Melting Point	0,05	°C	50	1100	High
Fabrication Time	0,15	Hours	15	80	Low

Table 3.6: Comparison of the fabricated antennas in various aspects.

Property	FFF	SLA	Metal-FFF	CNC
Avg. Dimensional Error (%)	1,12	0,74	1,47	0,53
Cost (\$)	22,6	65,6	440	182
Surface Roughness (μm)	7,79	5,32	9,99	1,32
Density (g/cm^3)	1,24	1,17	8,78	2,7
Weight (gr)	18,2	20,7	243	43,5
Tensile Strength (MPa)	60	65	207	310
Tensile Elongation (%)	6	6,2	30	12
Melting Point ($^{\circ}C$)	170	58,4	1070	582
Fabrication Time (hours)	16,5	16	75	28
Overall Rating	0,555	0,663	0,209	0,786

3.4 Closure

All data regarding the fabrication and physical condition of the antennas are tabulated and discussed in the previous sections. As seen from Table 3.6, CNC manufactured antenna is the best antenna with the highest overall rating. Therefore, the CNC fabrication method may be advantageous if cost, delivery period or weight is not an issue. The SLA fabrication produced the second highest rated antenna. If the user aims to have a light, accurate and relatively cheap fabrication, SLA may be the choice. FFF fabricated antenna is the third highest rated antenna with the lowest fabrication cost and weight. Metal-FFF has the lowest rating. But recalling it is a novel technology, this result is natural and expected to be improved over time.

The advantages and disadvantages of each fabrication method are elaborated in this chapter. The radiation and environmental tests are employed on the antennas and the results are discussed in the next chapter.

CHAPTER 4

ANTENNA RADIATION PARAMETERS & TEST CASES

In this chapter, radiation patterns and reflection coefficients (return loss) of the fabricated antennas are measured and discussed. Afterwards, military environmental condition tests are performed according to the MIL-STD-810H standard and the results are elaborated.

4.1 Antenna Radiation Pattern Measurements

4.1.1 Fundamentals of Antenna Radiation Pattern Measurements

Antennas are devices that are designed to either receive the electromagnetic waves that radiate in space or transmit electromagnetic waves into space. Antennas can transmit data kilometers away or vice versa. A graphical representation of the radiation characteristics of an antenna as a function of coordinates is called antenna radiation. In this representation, the concern is two or three dimensional spatial distribution of the radiated signals as a function along a path or constant radius [48]. An example of the 3D antenna radiation pattern can be seen in Figure 4.1 [49].

As seen from Figure 4.1, the electromagnetic field of an antenna is three-dimensional. But, in order to be able to analyze and compare the results it is beneficial to plot the data in a two-dimensional view. For this purpose, principal plane patterns are generated. These planes contain the maximum radiation levels with the electric or magnetic field vector. The plot of the radiation strength of the antenna on these planes constitutes a reliable representation of the performance of the antenna. These planes are called the *E* and *H*-planes. In Figure 4.1, the E-plane is the YZ-plane and the

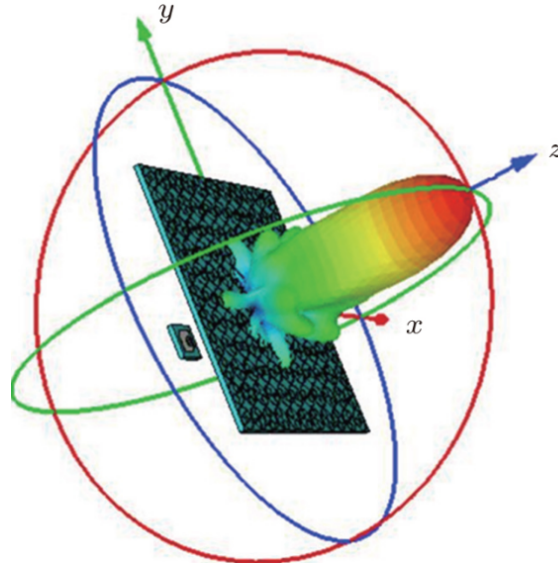


Figure 4.1: An example of the 3D radiation pattern of an antenna [49]

H-plane is the XZ-plane. E-plane is the plane containing the maximum radiation and also the *electric field vector* and H-plane is the plane containing the maximum radiation and the *magnetic field vector*. These two planes are perpendicular to each other due to their nature. These vector planes are regarded as functions of the space and time coordinates and they constitute the electromagnetic field of the antenna. The outline of the slices of the 3D representation of the electromagnetic field of the antenna through these planes generates the antenna radiation patterns in principle plane patterns. The theta angle is defined as the direction in these planes and spans the planes between 0° and $+180^\circ$. In Figure 4.1, the z-axis arrow indicates the direction of theta angle 0° in XZ or YZ-planes. In this chapter of the thesis, the performances of the antennas are analyzed by examining the E and H-plane radiation patterns of the antennas.

Antenna radiation patterns can be measured with various methods. Near-field or far-field methods are used in these measurements. In the far-field criterion, the antenna to be measured is generally placed on a tower or a high structure. The power of the signals radiated from the antenna is measured by the receiver antenna located in the far-field region. In the far-field criterion, this region is where electromagnetic fields behave approximately as plane waves. This distance is assumed to be kept beyond the maximum of the wavelength or Rayleigh distance, which is a function of maximum

antenna dimension and the wavelength, as a rule of thumb in high frequency applications. Obtained data from the receiver antenna is used to constitute the antenna radiation pattern [48].

In the near-field criterion, the antenna characteristics are measured in the near-field region, which is the region where electromagnetic fields do not behave as plane waves yet. In this region, electric and magnetic fields are closely coupled. Therefore they can not be measured separately. There are several different near-field antenna measurement methods. In this thesis study, a probe-based near-field measurement approach is used. In this method, a probe is used to sense the electromagnetic field near the test antenna. The antenna is mounted on a rotating platform within an anechoic chamber, which is a space designed with absorbing material that prevents reflections of electromagnetic waves, and the power of the signals radiated from the antenna in various directions is measured using a detector or multiple detectors. The antenna is rotated in small increments and data for each increment is collected. The collected data is used to create the plot of the antenna's radiation pattern [48]. In this thesis, Satimo Passive Measurement System is used for the antenna radiation pattern measurements, which is a probe-based near-field measurement system.

4.1.2 Measurements of the Fabricated Antennas

To start with, a simulation of the antenna via electromagnetic field simulation software is necessary. The antennas would be compared with the results of the simulations. For this purpose, CST 3D EM analysis studio is used in this thesis. The 3D representation of the X-Band horn antenna radiation pattern can be seen in Figure 4.2.

After the simulation is completed, the measurements for the produced antennas and CNC fabricated product can be carried out. The FFF, SLA, MFFF and CNC antennas are measured via Satimo Passive Measurement System. The FFF antenna fixed to its position in the anechoic chamber of the Satimo Measurement System can be seen in Figure 4.3. In the figure, it can be seen that the antenna is placed onto a rotating platform and it transmits signals. The yellow structures are the antennas that receive the signals radiated from the test antenna.

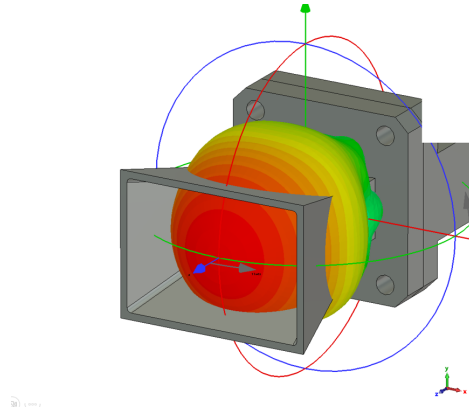


Figure 4.2: The simulation results of the X-Band horn antenna

After the measurements are completed, the results are tabulated and plotted in E and H-planes with the simulation results. The results are examined in three different frequencies; 8 GHz, 10 GHz and 12 GHz, which are the lower end, center and upper end of the bandwidth respectively.

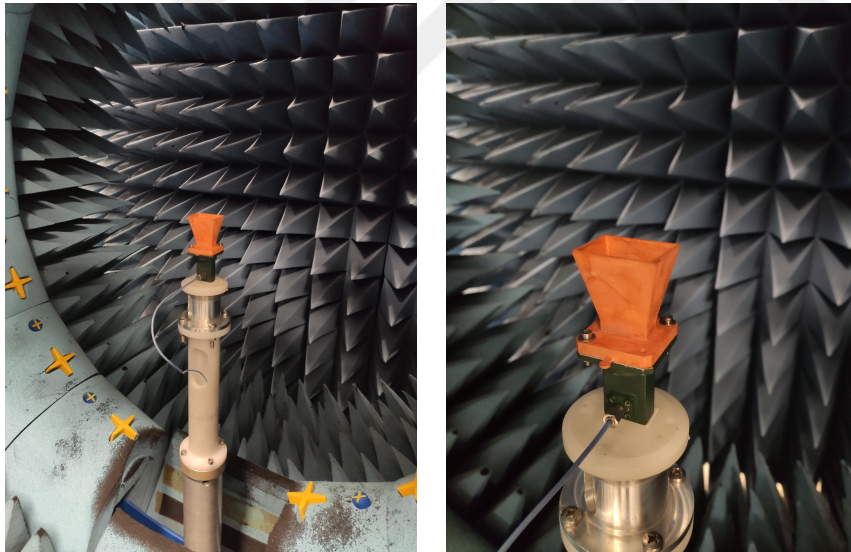


Figure 4.3: The antenna radiation pattern measurement process

The following figures are the antenna parameters measured in E-plane, which is the YZ-plane that can be seen in Figure 4.2. Figure 4.4 includes the antenna radiation patterns at the lower end of the bandwidth while Figure 4.5 includes the center and Figure 4.6 includes the upper end.

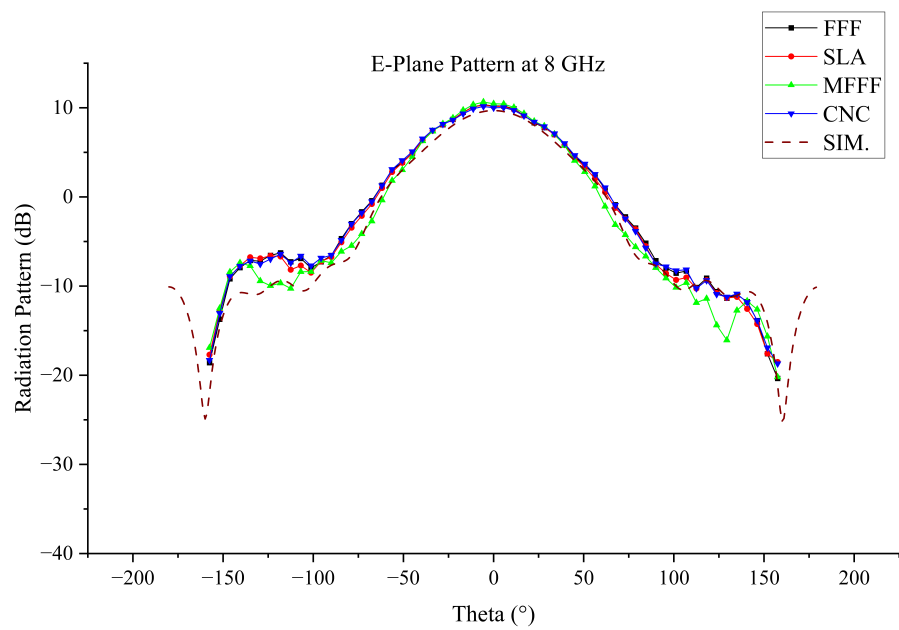


Figure 4.4: E-Plane Antenna Radiation Pattern at 8 GHz

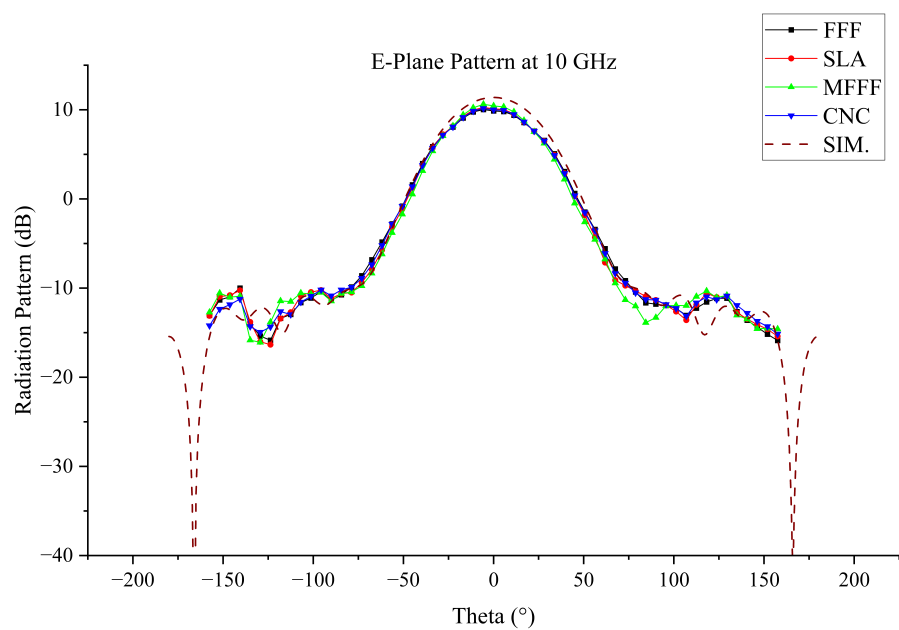


Figure 4.5: E-Plane Antenna Radiation Pattern at 10 GHz

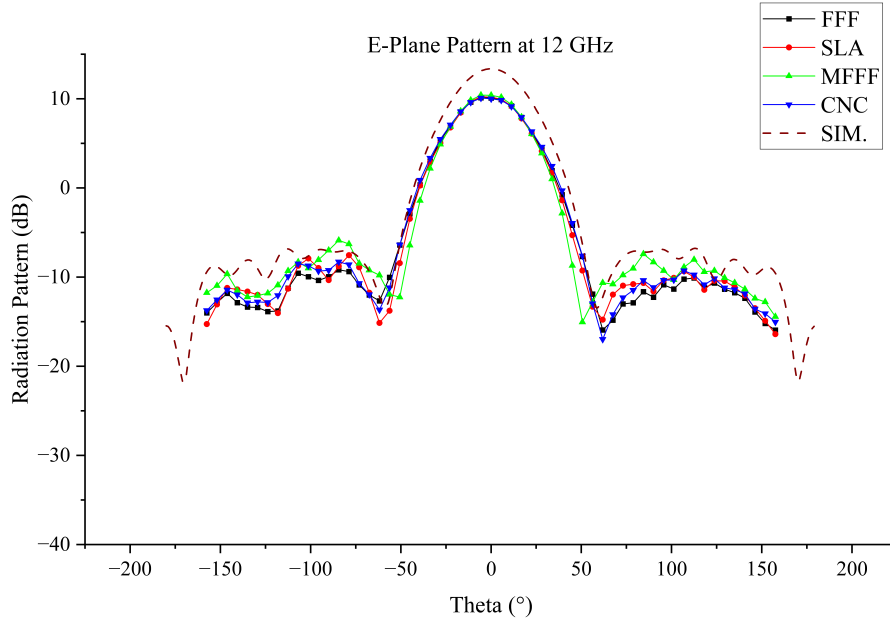


Figure 4.6: E-Plane Antenna Radiation Pattern at 12 GHz

The following figures are the antenna parameters measured in H-plane which is the XZ-plane that can be seen in Figure 4.2. Figure 4.7 includes the antenna radiation patterns at the lower end of the bandwidth while Figure 4.8 includes the center and Figure 4.9 includes the upper end.

As seen from the graphs, all antennas radiate quite conveniently according to the simulation results. Especially, at the center of the bandwidth (10 GHz) radiation is adjacent to the simulations both in E and H-planes. In the theta angle 0° , which is also called the maximum directivity of the antenna, at the center of the bandwidth, all antennas are considerably close to the simulation results and also to the gain value specified by the manufacturer, which is 10 dB. Noteworthy, while the FFF and SLA fabricated antennas performed similarly, the MFFF antenna results are slightly better. This situation may be due to the bulk metal material used in the MFFF method. Broad copper surfaces may affect the radiation quality.

If we focus on the lower and higher end of the bandwidth, at 8 GHz some antennas deliver higher levels of radiation than the simulated results. This situation is un-

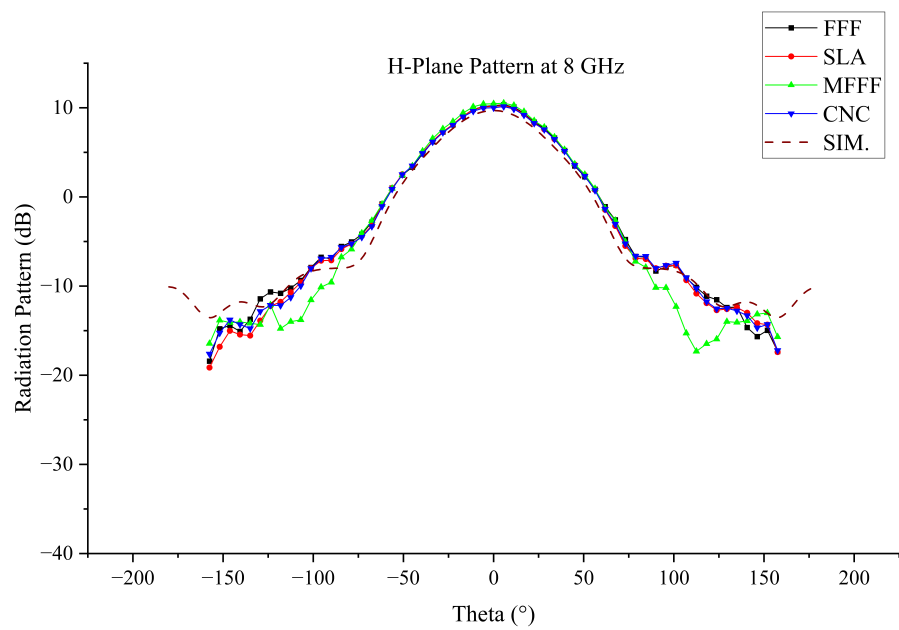


Figure 4.7: H-Plane Antenna Radiation Pattern at 8 GHz

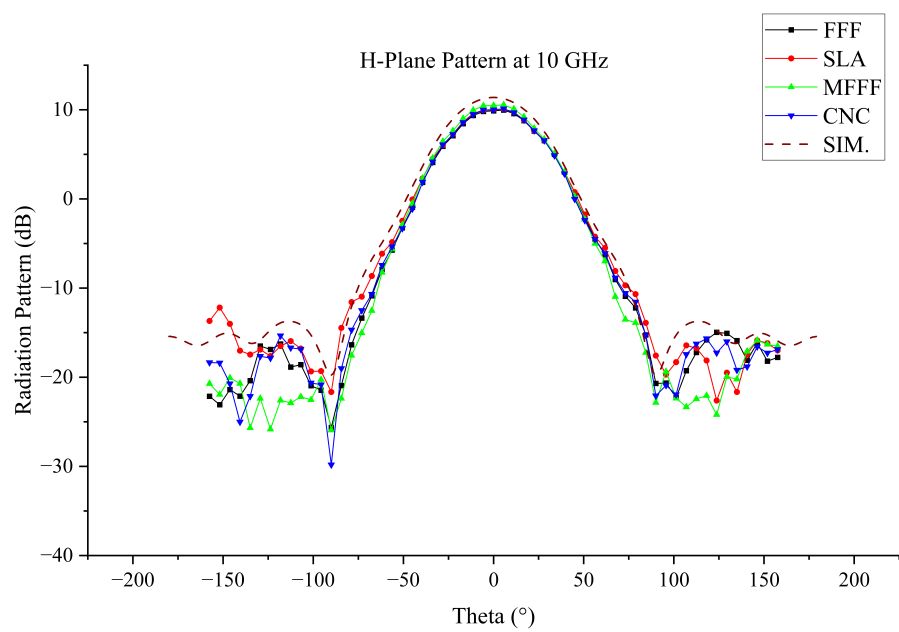


Figure 4.8: H-Plane Antenna Radiation Pattern at 10 GHz

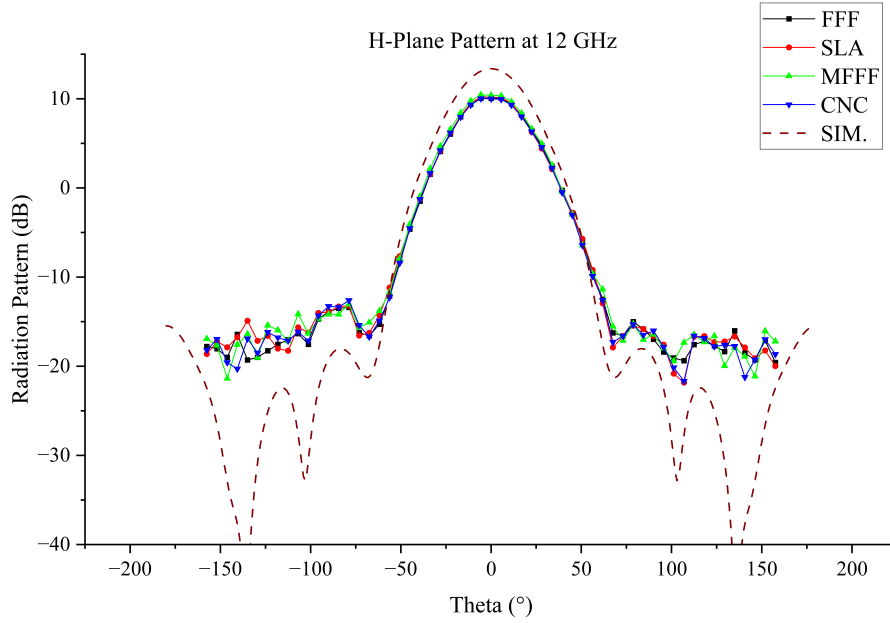


Figure 4.9: H-Plane Antenna Radiation Pattern at 12 GHz

usual and can be considered as an error since the simulation is done under perfect circumstances and in practice it is expected for the antenna to perform lower than the simulation in terms of gain. Various factors may be accounted for the mentioned error. These factors may be as follows.

- Errors of the simulation method
- Errors due to the measurement environment
- Errors due to the calibration of the measurement system

Nevertheless, such slight deviation between the simulation and measurements may be ignored. But at 12 GHz, antenna measurements are a bit lower than the simulation results which can be counted as a slight deficiency of the antennas. This situation may be due to the sensitivity of the antennas to surface roughness at higher frequencies. But overall, all antennas are operating convenient with the simulation results.

4.2 Return Loss Measurements

S (scattering) parameters express the input and output relationship between terminals of an electrical system. For example, if there are two ports called Port 1 and Port 2 in the system, then S_{12} parameter represents the power transferred from Port 2 to Port 1. S_{11} represents the power reflected from Port 1 to itself which is also called the reflection coefficient. In general, S_{ij} represents the power transferred from Port j to Port i in a network [50]. While S_{11} and S_{22} represents the reflected power, S_{12} and S_{21} represents the transferred power. S parameters are generally defined on a frequency domain and therefore these parameters are indicated as plots. S parameter measurements are performed due to two reasons. When energy is reflected, less energy is transmitted due to reflection, resulting in inefficient use and therefore costly RF energy and resources. Also, large amounts of reflected energy can damage circuit elements such as amplifiers.

S parameters are expressed by the decibel dB unit which is in the logarithmic base. For instance, if an antenna's S_{11} parameter is 0 dB , 100% of the power radiated from Port 1 is reflected to itself. If S_{11} parameter is -4 dB , 39,8% of the power radiated from Port 1 is reflected to itself. The following equation can be used for these calculations.

$$10^{-4dB/10} = 0,398 \quad (4.1)$$

If an antenna's S_{21} parameter is 0 dB , 100% of the power radiated from Port 1 is transported to Port 2. If S_{21} parameter is -2 dB , 63,1% of the power radiated from Port 1 is transported to Port 2. The following equation can be used for these calculations.

$$10^{-2dB/10} = 0,631 \quad (4.2)$$

S_{11} parameter is called the return loss. It is denoted by Γ . S_{11} parameter will be used in this thesis in order to compare the antennas' radiation performance.

S_{11} parameters of the FFF, SLA, MFFF and CNC fabricated antennas are measured

via a Rohde & Schwarz Vector Network Analyzer. The measurement results can be seen in Figure 4.10.

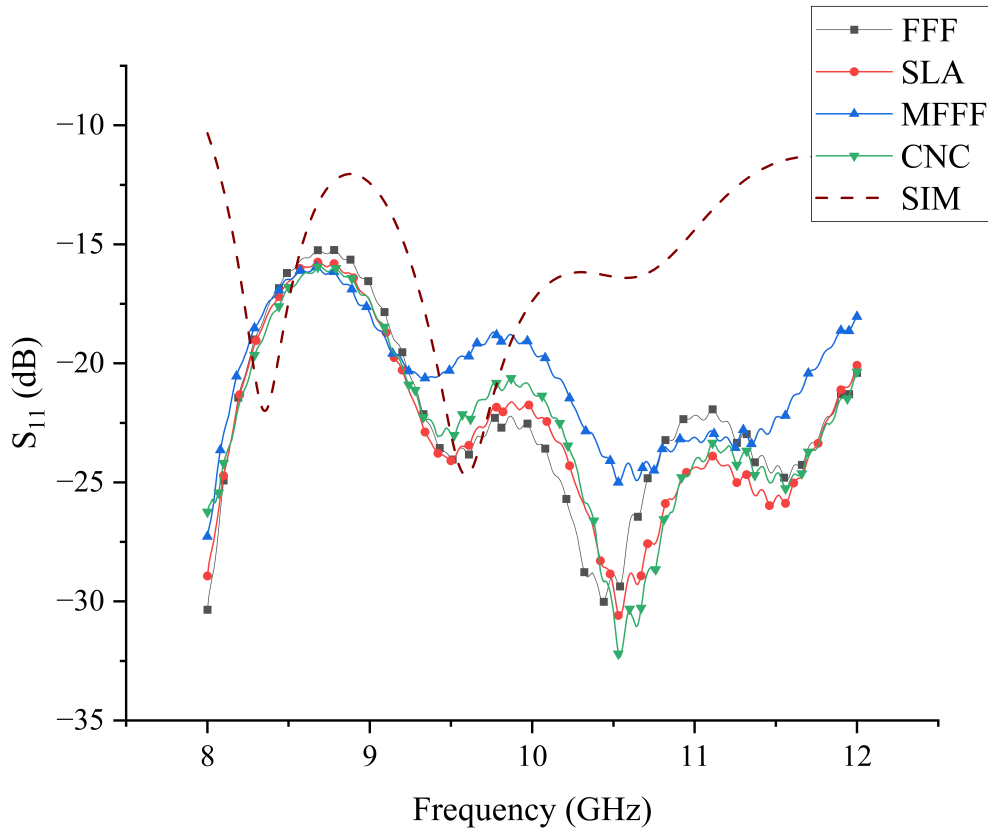


Figure 4.10: S_{11} measurements of the antennas with the CST simulation

As seen from the graph, there is some deviation from the simulation results with the antenna measurements. This is due to the limited imitation capability of the simulation software of the measurement environment. Nevertheless, the network analyzer results are fairly similar to the CNC fabricated product and also among themselves. At 15 dB, the return loss is 3,1% which means nearly 97% of the power is radiated properly which can be considered utterly eligible. As seen from the graphs, return loss is below 15 dB in most of the bandwidth. This verifies the antenna return loss is below 3% which can be considered as a minor deviation. Also, in the results it may be seen that the return loss is greater in Metal-FFF antenna than other antennas, but considering the results from the antenna radiation parameter measurements this

situation refers that the Metal-FFF antenna has less dielectric and conductor losses. Briefly, all antennas are concluded to be efficient with return loss properties below 15 *dB*.

The measurements show that the antennas have reasonably little return loss. Combining the results with the radiation pattern measurements, it is verified that all antennas are operating properly in terms of radio frequency. Thereafter, the military environmental condition tests can be applied to the antennas.

4.3 MIL-STD-810H Tests

The MIL-STD-810 standard is a military standard that defines the testing and design requirements of equipment used by the military to verify the equipment's ability to sustain environmental stress events throughout its lifetime. In the standard, the goal is stated as "Tailoring a materiel item's environmental design and test limits to the conditions that the specific materiel will experience throughout its service life, and establishing laboratory test methods that replicate the effects of environments on the materiel, rather than trying to reproduce the environments themselves" [1]. The standard is developed by the United States Department of Defense (DoD). MIL-STD-810H is often applied for commercial products even though it is developed especially for U.S. military applications. The suffix at the end stands for the revision of the standard. Revision H is the 9th and the latest revision and was published 31 January 31, 2019.

The standard defines 29 laboratory test methods used to test the strength of the material. These methods are not obligatory, but it is convenient to select the appropriate method and tailor the test to achieve the most realistic and accurate test data possible. The test methods can be seen in Table 4.1.

As stated earlier, all of these methods are not mandatory but the relevant test methods to the conditions related to the product's lifetime. The required tests are determined by two environmental testing specialists from Aselsan Inc. The following tests are conducted in the evaluation of additively manufactured antennas:

Table 4.1: MIL-STD-810H Test Methods.

Method 500.6 Low Pressure	Method 515.8 Acoustic Noise
Method 501.7 High Temperature	Method 516.8 Shock
Method 502.7 Low Temperature	Method 517.3 Pyroshock
Method 503.7 Temperature Shock	Method 518.2 Acidic Atmosphere
Method 504.3 Contamination by Fluids	Method 519.8 Gunfire Shock
Method 505.7 Solar Radiation	Method 520.5 Temperature, Humidity Vibration, and Altitude
Method 506.6 Rain	Method 521.4 Icing/Freezing Rain
Method 507.6 Humidity	Method 522.2 Ballistic Shock
Method 508.8 Fungus	Method 523.4 Vibro-Acoustic/Temperature
Method 509.7 Salt Fog	Method 524.1 Freeze / Thaw
Method 510.7 Sand and Dust	Method 525.2 Time Waveform Replication
Method 511.7 Explosive Atmosphere	Method 526.2 Rail Impact.
Method 512.6 Immersion	Method 527.2 Multi-Exciter
Method 513.8 Acceleration	Method 528.1 Mechanical Vibrations of Shipboard Equipment
Method 514.8 Vibration	

- Test Method 501.7 High Temperature: The antenna may be subjected to high temperatures during its life cycle. Therefore, a high temperature test will be applied according to the standard in order to see whether the geometry of the antenna or the coating will withstand the environmental condition.
- Test Method 502.7 Low Temperature: The antenna may be subjected to low temperatures during its life cycle. Therefore, a low temperature test will be applied according to the standard in order to see whether the geometry of the antenna or the coating will withstand the environmental condition.
- Test Method 503.7 Temperature Shock: The antenna may be subjected to sudden temperature changes during its life cycle. Therefore, a temperature shock

test will be applied according to the standard in order to see whether the geometry of the antenna or the coating will withstand the sudden environmental condition changes.

- Test Method 507.6 Humidity: The antenna may be subjected to humid/moist environments during its life cycle. Therefore, a humidity test will be applied according to the standard in order to see whether the geometry of the antenna or the coating will withstand the environments with high humidity ratios.
- Test Method 508.8 Fungus: The fungus test will be analyzed according to the standard in order to see if the antenna is a fungus nutrient ambient or not.
- Test Method 509.7 Salt Fog: The antenna may be subjected to marine environments during its life cycle and it is highly possible to confront humid ambiances with high salt content. Therefore, a salt fog test will be applied according to the standard in order to see whether the geometry of the antenna or the coating will withstand the environments with high salt and humidity ratios.
- Test Method 514.8 Vibration: The antenna may be subjected to high vibration conditions during its life cycle, especially in transportation. Therefore, a vibration test will be applied according to the standard in order to see whether the geometry of the antenna or the coating will withstand the environments with compelling amounts of vibration.
- Test Method 516.8 Shock: The antenna may be subjected to sudden acceleration changes during its life cycle, especially in transportation. Therefore, a shock test will be applied according to the standard in order to see whether the geometry of the antenna or the coating will withstand the environments with compelling amounts of shock.

4.3.1 Test Method 501.7: High Temperature

High temperatures can change and alter the physical properties of materials. The high temperature test aims to evaluate the effects of temperature rates higher than normal conditions on the materiel. The test is applied to materials exposed to high temperatures during their life cycle. Aging, solar radiation and actinic effects are not

considered in this method [1]. In overall, this test method is applied in order to clarify the effect of high temperature on the following matters [1]:

- Duration of the bind between materials with different expansion rates may alter.
- Lubricants may become less viscous and joints may lose lubrication due to the temperature.
- Dimensions of the material can change.
- Gaskets, seals, bearings and shafts may become distorted or display permanent coupling behavior.
- Resistance values of the materials can change. The stability of the electronic circuits may be varied.
- Transformers and electronic components may overheat and fail.
- Operating/release margins of relays and magnetic/thermally activated devices may change.
- Operating lifetime of the material may be shortened.
- Within sealed cases high pressure may be created.
- Explosives may melt and exude.
- Discoloration or cracking may occur.
- Adhesives may fail.

There are three temperature testing procedures related to High Temperature Test Method:

Procedure I – Storage - The assessment of the effects of high temperature while the device/material is not in use.

Procedure II – Operation - The assessment of the effects of high temperature while the device/material is in operation.

Procedure III – Tactical-Standby to Operational - The assessment of the ability of a device/material that has been exposed to a high-temperature environment to become operational in a short period.

In the standard, high temperature areas are divided into two: Basic Hot (A2) and Hot Dry (A1). Basic Hot environments have 30-43°C ambient temperature. Southwestern United States, northwestern Mexico, central/western Australia, Saharan Africa, South America, southern Spain, and southwest and south-central Asia are examples of Basic Hot environments. Hot Dry environments have 32-49°C ambient temperature. Southwest and south-central Asia, the southwestern United States, Saharan Africa, central and Western Australia, and northwestern Mexico are examples of Hot Dry environments. It is recommended to test the devices that will operate in mentioned areas according to Method 501.7.

Procedure I will be applied to the additively manufactured test coupon parts since the antennas are monolithic and compact devices and there will be no difference between operational mode and storage mode. Also, becoming operational right after exposure to high temperatures is not expected from the antenna. Therefore, the following steps will be applied to the printed test coupons:

Step 1. Place the test coupon in its storage/operational configuration and install it in the heating chamber.

Step 2. Modify the chamber convenient to the required test conditions for the selected exposure type. Make sure you take enough time for temperature stabilization of the test item.

Step 3: Expose the materiel to the cyclic or constant temperature at a rate not exceeding 3°C/min and maintain. For cyclic exposure perform the test 7 times as 24 hours, for constant temperature maintain the temperature 2 hours after the stabilization of the temperature. The additional two hours of test can help ensure unmeasured internal components reach stabilization, but since the antennas have no internal components the additional period is not necessary.

Step 4. At the completion of the test, set the chamber temperature as the ambient temperature and maintain it until the test item temperature is stabilized.

Step 5. Perform a visual examination and operational checkout of the tested item and record the results.

The temperature exposure graph of Procedure I can be seen in Figure 4.11.

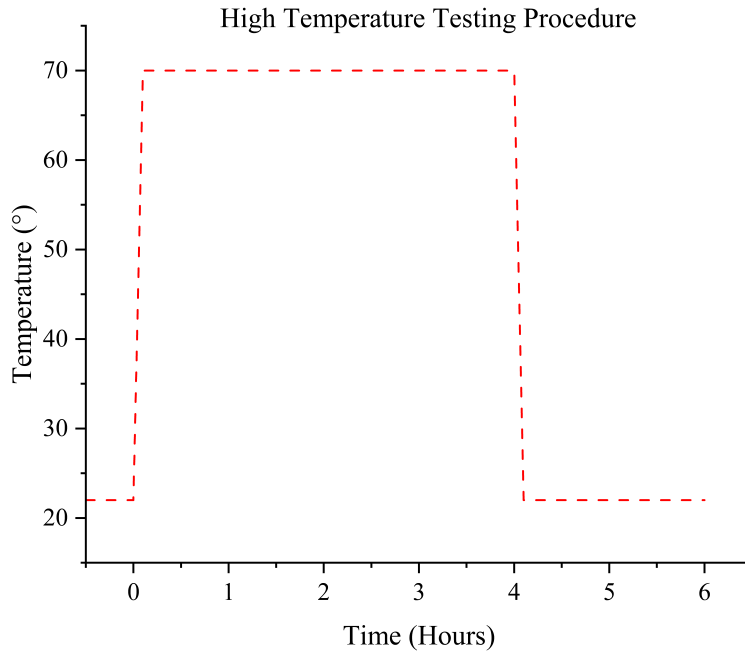


Figure 4.11: Graphical representation of Method 501.7 Procedure I

In our case, the test temperature is selected as +70°C. The coupons were exposed to a constant high temperature for 6 hours convenient to the standard procedure. The graph of the test temperature can be seen in Figure 4.12. The green line denotes the set point values which are the process variables desired to be maintained. The red line is constituted by the output values of the thermocouple placed inside the test chamber.

Before and after the test, images of the coupons are taken. Also, for comparison, the conductivity levels of the coupons are measured since conductivity is directly related to the radiation quality. In one centimeter distance on the surface of the coupons, the resistance values are read between 0,6-1 Ω . For the measurement a multimeter is used. The measurement setup can be seen in Figure 4.13. Figure 4.14 shows the test coupons before and after the test is applied.

As seen from Figure 4.14, there is no visually observable degradation available. Also,

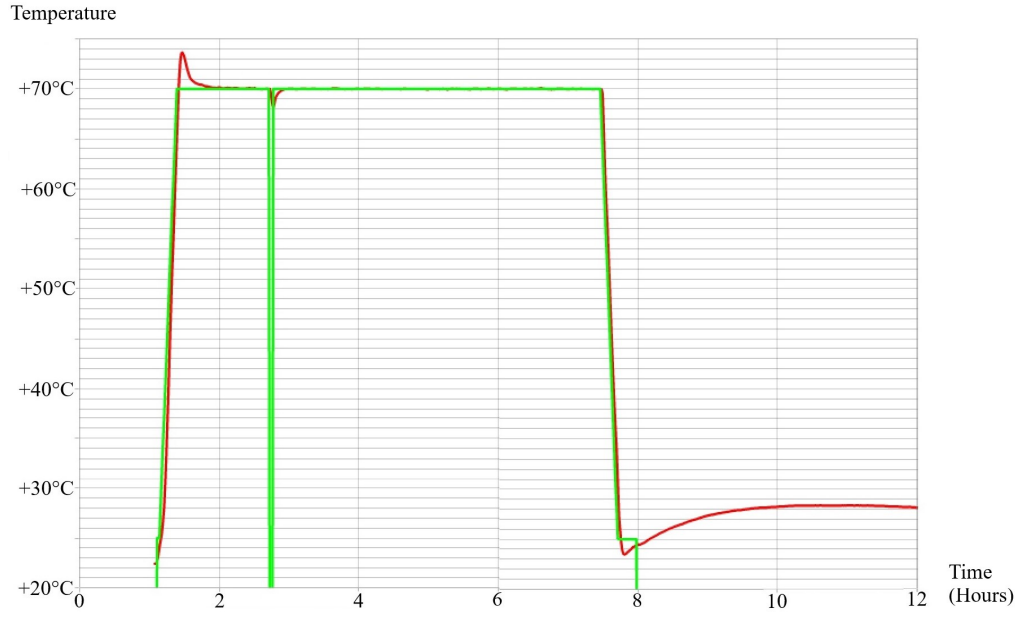


Figure 4.12: High temperature testing procedure



Figure 4.13: The resistivity measurement setup

the resistivity values are the same as the pre-test values. But, in order to prove that the coupons passed the high temperature test, a return loss measurement of the antennas which are exposed to the high temperature test method is necessary. Therefore, all AM antennas are exposed to the procedure and S_{11} parameter measurements are

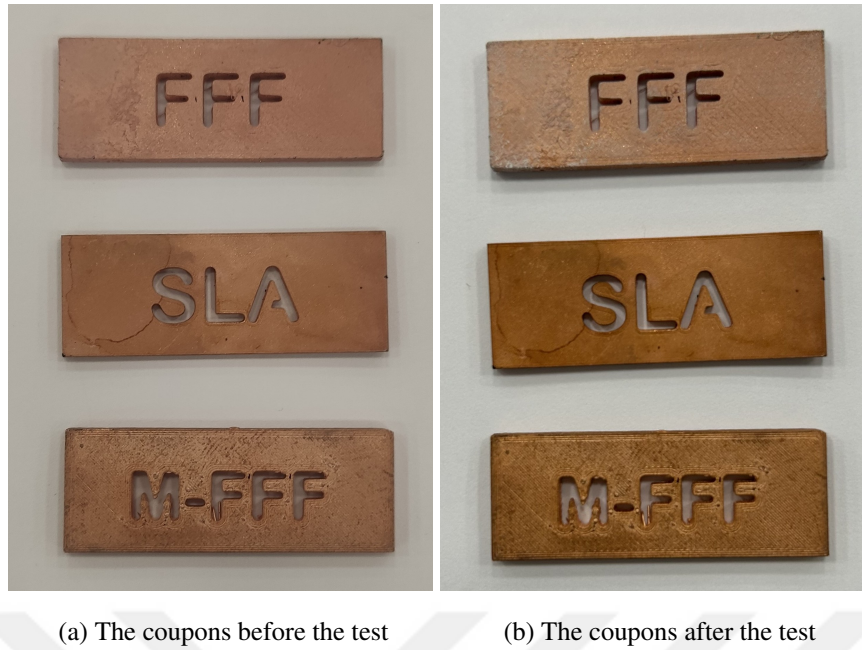


Figure 4.14: Test coupons before and after the high temperature test

conducted. The S_{11} parameters of the antennas can be seen in Figure 4.15.

As seen from Figure 4.15, all antennas provide results below -15 dB , which confirms the antennas are still operational after the test. It can be realized that there is a deviation between the before and after test results. The connector used for the test is changed since the first connector was not available at that moment and this situation is believed to be the source of this deviation.

4.3.2 Test Method 502.7: Low Temperature

Low temperatures can change and alter the physical properties of materials. The low temperature test aims to evaluate the effects of temperature rates lower than normal conditions on the materiel. The test is applied to materials exposed to low temperatures during their life cycle. It does not cover the high altitude, low temperature environment associated with an unpressurized aircraft at altitude. In overall, this test method is applied in order to clarify the effect of low temperature on the following matters [1]:

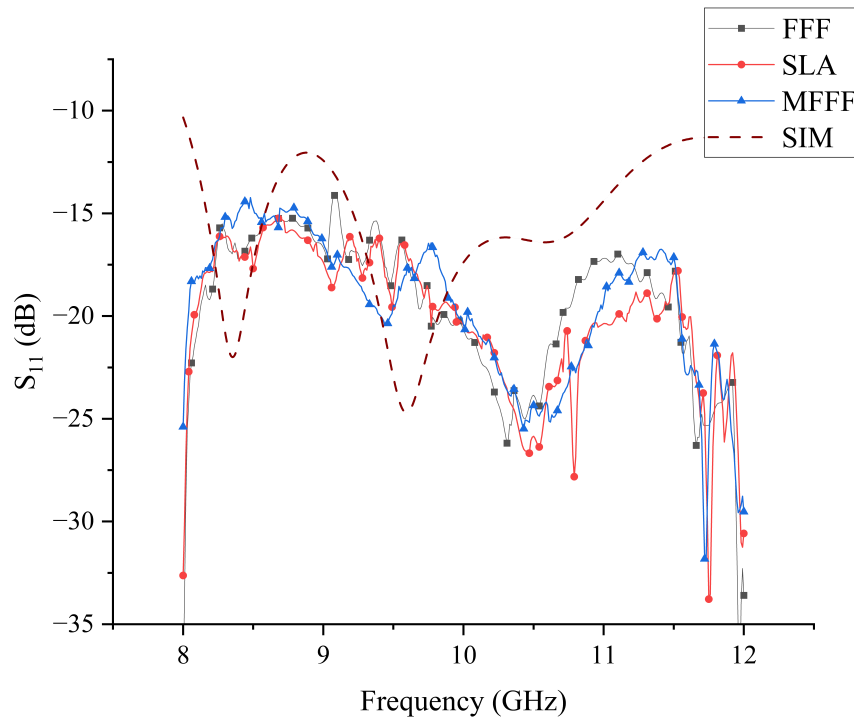


Figure 4.15: S_{11} measurements after high temperature test

- Hardening and embrittlement of the materiel.
- Duration of the bind between materials with different expansion rates may alter.
- Lubricants may become less viscous and joints may lose lubrication due to the temperature. In addition, gelation may occur in fuels.
- Changes in electronic components such as resistors, capacitors, transformers and other electromechanical components.
- Shock mounts may become stiffer.
- Cracking and crazing, change in impact strength and reduced strength may be obtained.
- Static fatigue of restrained glass can occur.
- Condensation and freezing of water in/on the materiel can affect the test item.

- Dexterity, hearing, and vision of personnel wearing protective clothing can be decreased.
- Burning rates of the materials may change.

There are three temperature testing procedures related to Low Temperature Test Method:

Procedure I – Storage - The assessment of the effects of low temperature while the device/material is not in use.

Procedure II – Operation - The assessment of the effects of low temperature while the device/material is in operation.

Procedure III – Manipulation - The assessment of the ability of an assembling, operating and dismantling device/material that has been exposed to a low-temperature environment by personnel wearing heavy, cold-weather clothing.

In the standard, low temperature areas are divided into three: Basic Cold (C1), Cold (C2) and Severe Cold (C3). Basic Cold environments have -21 to -32°C ambient temperature. Most of Europe, the northern contiguous US, coastal Canada and high latitude coasts are examples of Basic Cold environments. Cold environments have -37 to -46°C ambient temperature. Canada, outer Alaska, Greenland, Northern Scandinavia, Northern Asia, the Alps, Himalayas are examples of Cold environments. Severe Cold environments have -51°C ambient temperature as referred in the standard. Interior Alaska, Yukon (Canada), the interior of Northern Canadian Islands, the Greenland ice cap and Northern Asia are examples of Cold environments. It is recommended to test the devices that will operate in mentioned areas according to Method 502.7.

Procedure I will be applied to the additive manufactured test coupon parts since the antennas are monolithic and compact devices and there will be no difference between operational mode and storage mode. Also, it is not expected the authorized personnel to have difficulty in assembling, operating and dismantling the antenna. Therefore, the following steps will be applied to the printed test coupons:

Step 1. Place the test coupon in its storage/operational configuration and install it in the low temperature chamber.

Step 2. Modify the chamber convenient to the required test conditions for the selected exposure type. Make sure you take enough time for temperature stabilization of the test item and also do not exceed $3^{\circ}\text{C}/\text{min}$ temperature change rate.

Step 3: After the stabilization, maintain the storage temperature for the period selected as convenient in the test plan. If the test item has internal parts, consider maintaining additional exposure time.

Step 4. At the completion of the test, set the chamber temperature as the ambient temperature and maintain it until the test item temperature is stabilized.

Step 5. Perform a visual examination and operational checkout of the tested item and record the results.

The temperature exposure graph of Procedure I can be seen in Figure 4.16.

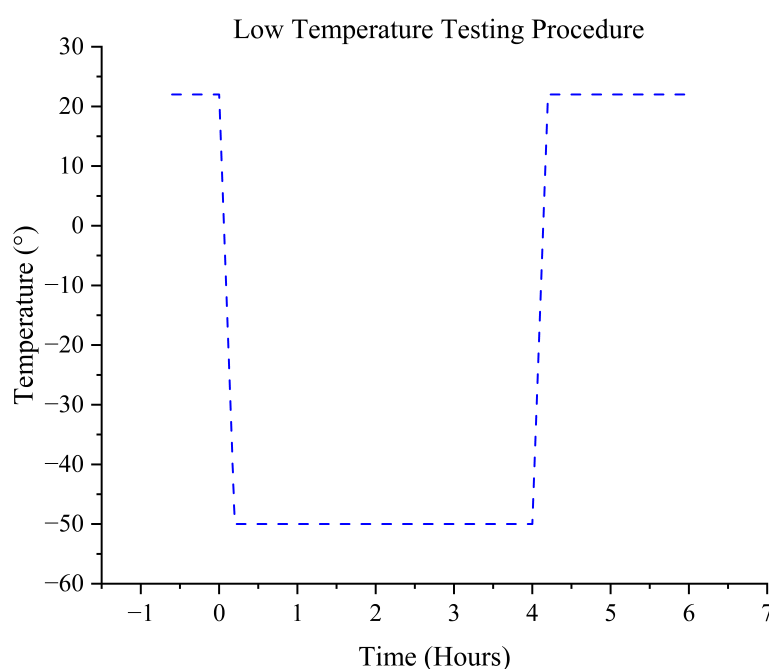


Figure 4.16: Graphical representation of Method 502.7 Procedure I

In our case, the test temperature is selected as -50°C . The coupons were exposed to a constant low temperature for 6 hours convenient to the standard procedure. The

graph of the test temperature can be seen in Figure 4.17. The green line denotes the set point values which are the process variables desired to be maintained. The red line is constituted by the output values of the thermocouple placed inside the test chamber.

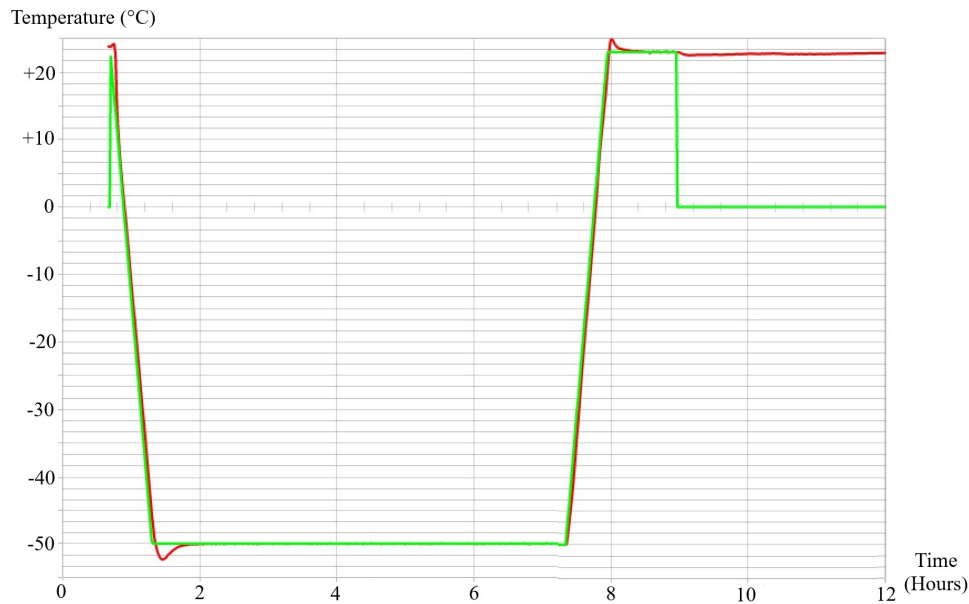


Figure 4.17: Low temperature testing procedure

Before and after the test, images of the coupons are taken. Also, for comparison, the conductivity levels of the coupons are measured since conductivity is directly related to the radiation quality. In one centimeter distance on the surface of the coupons, the resistance values are read between 0,6-1 Ω . Figure 4.18 shows the test coupons before and after the test.

As seen from Figure 4.18, the FFF and SLA fabricated antennas have some color change, while the MFFF fabricated antenna nearly preserved its overall look. Also, the resistivity values of the FFF and SLA fabricated coupons are about 4 Ω , the MFFF coupon still has 0,6 Ω resistivity. So, it can be concluded while the MFFF coupon passed the test, the FFF and SLA coupons have some degradation which is considered a failure since the surface quality could not be maintained.



(a) The coupons before the test

(b) The coupons after the test

Figure 4.18: Test coupons before and after the low temperature test

4.3.3 Test Method 503.7: Temperature Shock

The aim of the temperature test method is to assess if the item can withstand rapid temperature changes. The test essentially focuses on the surfaces of the materiel. The test does not cover shock experienced by materiel transferred between two liquids or air and a liquid. In overall, this test method is applied in order to clarify the effect of temperature shock on the following matters [1]:

- Glass vials or optical material may be shattered.
- Binding of the moving parts may be altered and slackened.
- Solid pellets or grains in explosives can crack.
- Differential contraction or expansion rates in dissimilar materials can cause cracks and induced strain rates.
- Components may deform or even fracture.
- Surface coatings can crack.

- Sealed compartments may cause leakage.
- Insulation protection may fail.
- Chemical agent protection may fail.
- Electrical and electronic components may change.
- Electronic or mechanical failures can occur due to rapid water or frost formation.

There are four temperature testing procedures related to Temperature Shock Test Method:

Procedure I-A - One way shock from constant extreme temperature – At least one shock for each appropriate condition, such as low to high temperature or high to low temperature.

Procedure I-B - Single cycle shock from constant extreme temperature – One shock for low-to-high temperature and one shock for high to low temperature.

Procedure I-C - Multi-cycle shocks from constant extreme temperature - At least three shocks at each condition, such as four transitions from cold to hot temperature and four transitions from hot to cold temperature.

Procedure I-D - Shocks to or from controlled ambient temperature – Follows the previous procedures, but all shocks are to or from controlled ambient conditions.

Procedure I-C will be applied to the additive manufactured test coupon parts since it is the most comprehensive method and covers all possible environment types that the antenna can operate:

Step 1. Place the test coupon in its storage/operational configuration. Set the chamber temperature to the high or low temperature extreme specified in the test plan and maintain the temperature change rate below 3°C/min. Wait until the temperature is stabilized.

Step 2. In less than one minute, transfer the temperature of the test item to the other extreme temperature value that will produce the thermal shock specified in the test plan. Wait until the temperature is stabilized.

Step 3. Evaluate the shock effects on the item if it is required in the test plan.

Step 4. In less than one minute, transfer the temperature of the test item to the first extreme temperature value. Wait until the temperature is stabilized. Evaluate the thermal shock effects if required.

Step 5. Repeat steps 2-4 as many times as specified in the test plan. At least additional two cycles must be applied.

Step 6. Transfer the test item to standard ambient conditions.

Step 7. Visually examine the test item and if required in the test plan perform an operational check.

In our case, the test extremities are selected as -50°C and $+70^{\circ}\text{C}$. The test coupons were exposed to these extreme temperatures for 2 hours. The cycle is repeated three times convenient to the standard procedure.

Before and after the test, images of the coupons are taken. Also, for comparison, the conductivity levels of the coupons are measured. In one centimeter distance on the surface of the coupons, the resistance values are read between $0,6-1\ \Omega$. Figure 4.19 shows the test coupons before and after the test.

As seen from Figure 4.19, there is no visually observable degradation available. Also, the resistivity values are the same as the pre-test values. But, in order to prove that the coupons passed the temperature shock test, a return loss measurement of the antennas which are exposed to the temperature shock test method is necessary. Therefore, all AM antennas are exposed to the procedure and S_{11} parameter measurements are conducted. The S_{11} parameters of the antennas can be seen in Figure 4.20.

As seen from Figure 4.20, all antennas provide results below $-15\ \text{dB}$, which confirms the antennas are still operational after the test.

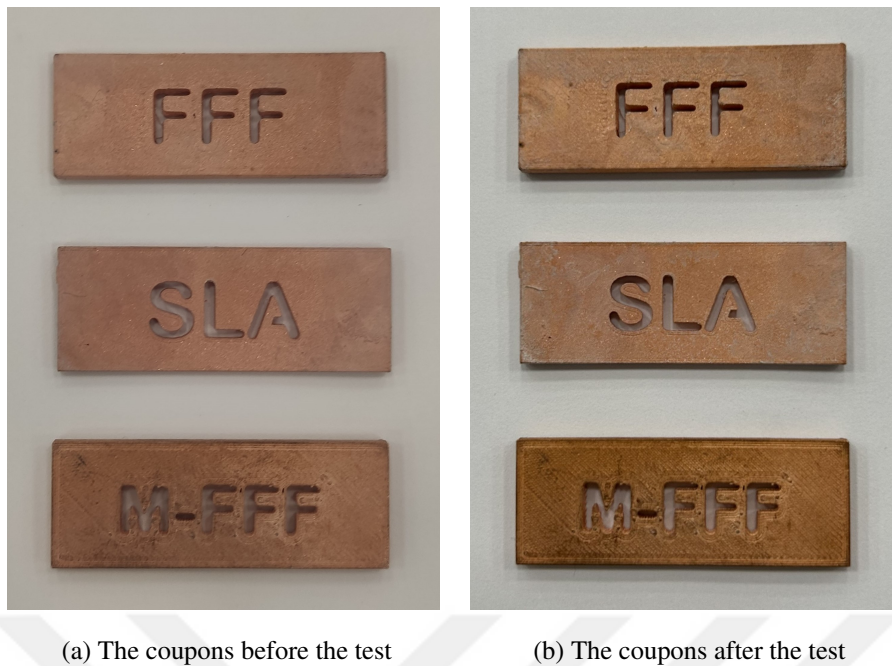


Figure 4.19: Test coupons before and after the temperature shock test

4.3.4 Test Method 507.6: Humidity

The humidity test aims to evaluate the effects of warm, high levels of humidity environment on the test item. This method is applied to the systems that will be stored or operated in such environments during their life cycle. In overall, this test method is applied in order to clarify the effect of high humidity on the following matters [1]:

- Oxidation or galvanic corrosion of metals may occur.
- Chemical reactions' variety and rapidity may increase.
- Chemical breakdown of organic and inorganic surface coatings may occur.
- Friction coefficients of the materials can change which may result in binding or sticking.
- Materials can swell and explosives/propellants can deteriorate due to absorption effects.
- Physical strength may decrease.

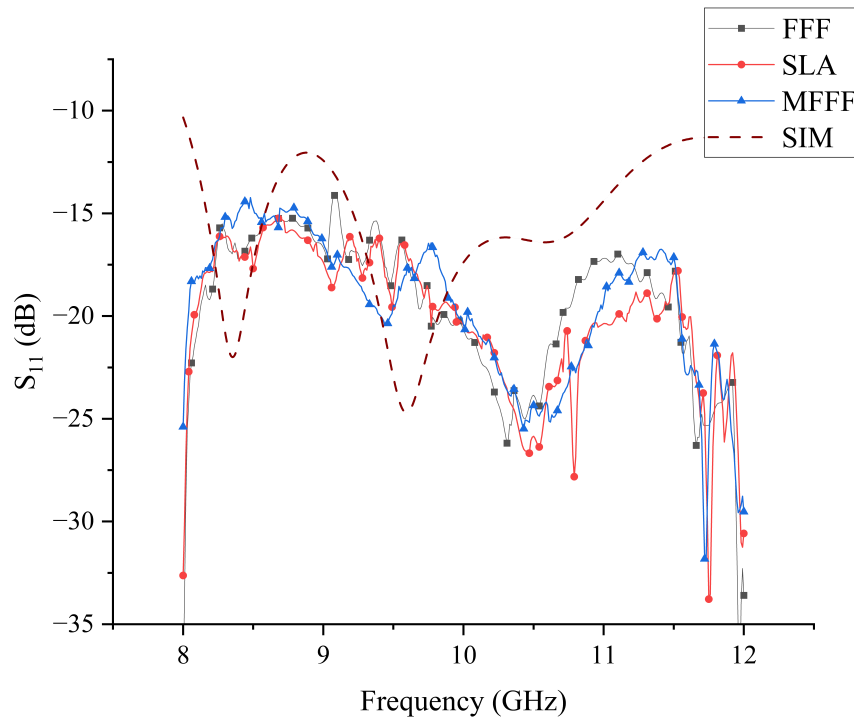


Figure 4.20: S_{11} measurements after temperature shock test

- Electrical and thermal insulating characteristics may alter.
- Composite materials may delaminate.
- Lubricants may deteriorate.
- Electrical short circuits may occur.
- Fogging of optical surfaces may occur.
- Thermal transfer characteristics may change.

There are two different testing procedures related to Humidity Test Method:

Procedure I – Induced (Storage & Transit) and Natural Cycles - Once a cycle is selected, perform the storage and transit part first and continue with the corresponding natural environment portion of the cycle. Procedure I includes 6 cycles divided as:

(1) three unique cycles that represent conditions that can occur during storage or transit

(2) three unique natural environment cycles that are performed on the materiel which are open to the environment.

Procedure II – Aggravated – This test method exposes test items to more extreme temperature and humidity conditions than those found in nature. These tests with such temperature levels last a shorter period than natural cycles. An advantage of this procedure is quicker test results.

There are several test conditions mentioned in the standard. These conditions and where these conditions can be observed are as follows:

Specific test temperature – Humidity values are usually selected from the requirements in the projects or documents. If this data is not available, the values can be based on the areas in which the test item will be used.

Constant High Humidity (Cycle B1) – This humidity condition is generally found in tropical areas. The environmental condition is constantly wet or damp for many days at a time. This humidity level can exist for 25 to 30 days each month in the most humid areas of tropical regions.

Cycle high Humidity (Cycle B2) – This humidity condition is found in open tropical areas where radiation is a factor. In the test, it is allowed to conduct the natural cycle with solar radiation simulation if the item is exposed to direct solar radiation. The frequency and duration of occurrence are fundamentally the same as the Constant High Humidity Cycle (Cycle B1).

Hot-humid (Cycle B3) – Along a coastal strip below five miles wide, intense dew point conditions occur 10 to 15 times a year. This cycle is generally used to test the parts/devices used in the Persian Gulf and Red Sea regions. It is not applicable to use for worldwide exposure requirements.

Procedure II will be applied to the additively manufactured test coupon parts since this procedure can produce quicker results in more severe conditions and is more straightforward. Therefore, the following steps will be applied to the printed test

coupons:

Step 1. Place the test coupon in its required configuration and install it in the chamber. Adjust the temperature to $23\pm 2^{\circ}\text{C}$ and 50 ± 5 percent RH, and maintain at least 24 hours.

Step 2. Adjust the chamber temperature to 30°C and the relative humidity to 95 percent.

Step 3. Expose the material to 24-hour cycles ranging from $30\text{-}60^{\circ}\text{C}$ at least ten times. It is beneficial to conduct an operational check at the end of the fifth and tenth cycles.

Step 4. At the completion of at least 10 successful cycles, adjust the temperature and humidity to $23\pm 2^{\circ}\text{C}$ and 50 ± 5 relative humidity and maintain until the test item is stabilized.

Step 5. Perform a visual examination and operational checkout of the tested item and record the results.

The procedure is conducted as specified in the military standard. 10 cycles of 24 hours in the $30\text{-}60^{\circ}\text{C}$ temperature range at 95% relative humidity is applied on the test coupons. The graph of the testing procedure can be seen in Figure 4.21. The green line and the blue line denotes the temperature and humidity set point values respectively. The red line is constituted by the output values of the thermocouple placed inside the test chamber. The yellow line is constituted by the humidity values measured inside the chamber during the test.

Before and after the test, images of the coupons are taken. Also, for comparison, the conductivity levels of the coupons are measured. In one centimeter distance on the surface of the coupons, the resistance values are read between $0,6\text{-}1\ \Omega$. Figure 4.22 shows the test coupons before and after the test.

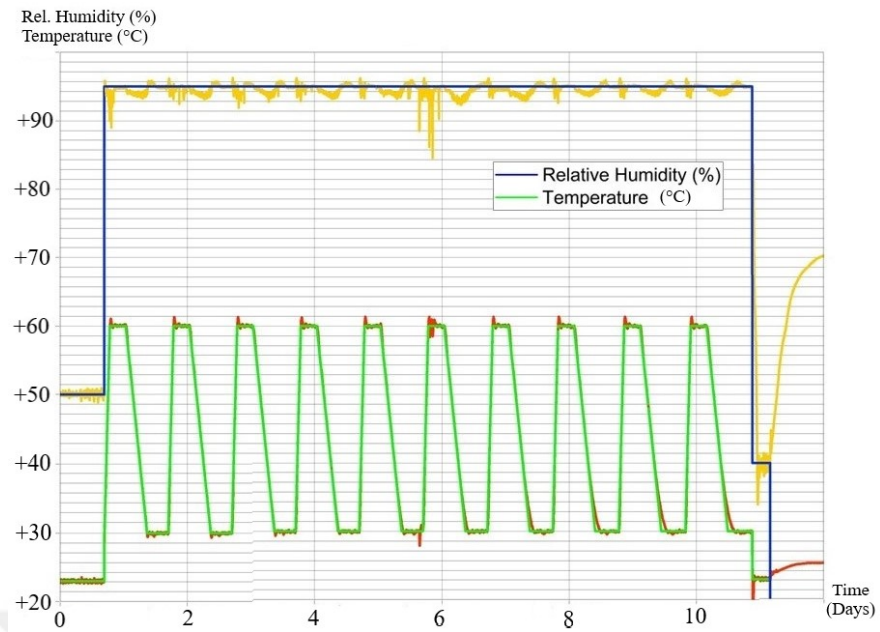


Figure 4.21: Humidity testing procedure



(a) The coupons before the test

(b) The coupons after the test

Figure 4.22: Test coupons before and after the humidity test

4.3.5 Test Method 508.8: Fungus

Fungal growth may have long term impacts on a wide range of materials including metals, plastics, fabrics, etc. The aim of the Fungus Test is to assess the vulnerability of the material to fungal growth, the dominant species and how rapidly the fungus will grow. Since chemical and biological breakdown is a function of temperature and humidity, they must be considered in the design phase. In overall, this test method is applied in order to clarify the effect of fungal growth on the following matters [1]:

- The fungus breaks down the material and alters its physical properties. Several natural and synthetic materials can be affected.
- Fungal growth on surface deposits of contaminants can damage the underlying material.
- Metabolic waste products excreted by fungus may cause corrosion, etching and degradation.
- The fungus may form undesired electrical connections across insulating materials and vice versa.
- The fungus may alter the electrical properties of the materials.
- The fungus can affect light transmission through an optical system.

There is only one testing procedure related to Fungus Test Method:

Step 1. Place the test coupon in the test chamber.

Step 2. Maintain the test item at $30\pm 2^{\circ}\text{C}$ and 90-100% relative humidity for at least 4 hours.

Step 3: Place cotton control strips with mixed fungus spores onto the test item.

Step 4. Check if at least 90% of the inspected area is covered by fungus. If not, repeat the test for 7 more days.

Step 5. Perform a visual examination and operational checkout of the tested

item. If at least 90% of the test strip located level is covered with fungus, it can be said that the materiel is fungus nutrient.

Since the necessary equipment for the fungus test is not present in the facility, the test military handbook (MIL-HDBK-454B) will be examined [51]. The materials used for antenna production are polylactic acid, photopolymers used in the resin material and copper. The polymer antennas are coated with copper as well. In the handbook, it is stated that fungus nutrient materials can be used untreated within hermetically sealed enclosures [51]. The copper coating forms the hermetically sealed enclosure and even if the polymer used underneath the plating is fungus nutrient, the fungus will not be able to grow on the surface for all three antennas. Also, metals are considered fungus inert material in the handbook [51] which confirms the MFFF antenna can pass the fungus test. Therefore, one can conclude that all three antennas can pass the fungus test.

4.3.6 Test Method 509.7: Salt Fog

The aim of the salt fog test is to evaluate the durability of the materiel against salty environments. Salt can have physical, electrical and corrosive effects on the subjected materiel. This test method is applied to the systems that will be stored or operated in such environments during their life cycle and is especially significant in naval applications. In overall, this test method is applied in order to clarify the effect of high humidity on the following matters [1]:

- Electrochemical reactions can cause corrosion.
- Acidic or alkaline solutions can form due to salt ionization in water.
- Electrical material can corrupt due to salt deposits.
- Coatings may become conductive.
- Moving parts can be clogged or bonded due to salt deposition.
- The paint of the material may swell if electrolysis occurs.

There is only one testing procedure related to Humidity Test Method:

Step 1. Place the item in the chamber and set the chamber temperature to 35°C. Maintain the item for at least two hours.

Step 2. Atomize a salt solution into the chamber for 24 hours or 48 hours. The testing time can be adjusted according to the testing plan.

Step 3. Let the item dry at ambient temperature at a relative humidity below 50% for the amount of time chosen in the previous step.

Step 4. If the 24 hours cycle is chosen, repeat the cycle at least one more time. If the 48 hours cycle is chosen proceed to the next step.

Step 5. Complete the physical and electrical checks. After the analysis, gently wash the materiel in running water to get rid of the salt deposits.

Step 6. Perform a visual examination and operational checkout of the tested item. Look for corrosion or any other surface degradation.

The procedure is conducted as specified in the military standard. The test is conducted with the water solution consisting of 5% salt. Before the atomization, the item is maintained at 35°C for two hours for stabilization. After the stabilization, the item is exposed to the solution for 24 hours and dried at ambient temperature. The cycle is performed two times.

Before and after the test, images of the coupons are taken. Also, for comparison, the conductivity levels of the coupons are measured. In one centimeter distance on the surface of the coupons, the resistance values are read between 0,6-1 Ω . Figure 4.23 shows the test coupons before and after the test.

As seen from Figure 4.23, there are high degrees of degradation on all coupons. Also, the resistivity values are greater than a million Ω for the FFF and SLA coupons. The resistivity values for the MFFF coupon is ranging between 5 and 40 Ω which can not be considered a good conductive surface. Therefore, it can be concluded all three



Figure 4.23: Test coupons before and after the salt fog test

coupons failed the test.

4.3.7 Test Method 514.8: Vibration

Test vibration test method is developed in order to verify the product can withstand the vibrations encountered in the lifetime of the product. This test method is applied in order to clarify the effect of vibration on the following matters [1]:

- Fasteners or components can loose.
- Electrical contacts can become intermittent or permanently disconnected.
- Electrical shorts may be encountered.
- Seals may be deformed.
- Components may fail.
- Misalignment of the components may occur.
- Structures may crack or break.

- The particles of the failed components may migrate.

In the standard, there are four different test methods. But, there are numerous environmental vibration categories. The standard guides the user to select the correct combination for the methods and the categories. These procedures require a tailored vibration profile that reflects the life cycle of the tested item. Also, the standard offers alternative product vibration testing services that don't require tailoring in the annex section.

In our case, Vibration Testing Category 24 will be applied to the material from the annex section. This test is also called as Minimum Integrity Test (MIT). This test can be used for the item at the beginning of the design or if the environmental conditions are unknown. Since the environment of the designed antenna is unknown the selection is convenient. But worth mentioning, tailored tests are generally preferred over minimum integrity tests. The vibration profile of the test can be seen in Figure 4.24.

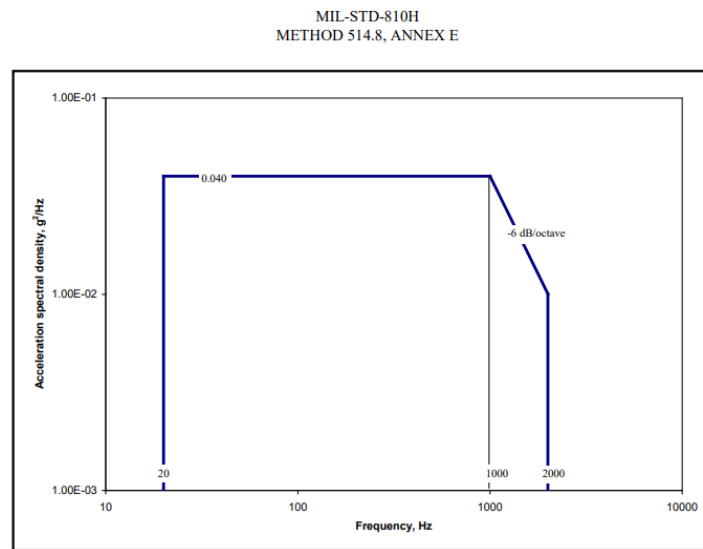


Figure 514.8E-1. Category 24 - General minimum integrity exposure.
(Test duration: One hour per axis; rms = 7.7 g's)

Figure 4.24: Minimum integrity testing procedure [1]

This graph is a demonstration of the severity distribution in the frequency domain of the vibrations created by the test setup. The setup can generate random vibrations suitable to this power spectral density graph.

For the test, the antennas were fastened to a test jig by convenient bolts and washers and locking liquid. The jig is fastened to the excitation platform afterwards. The testing setup can be seen in Figure 4.25. The random vibration test suitable with the minimum integrity test method is carried out for three hours. No degradation is observed in the parts. Therefore, it can be concluded that all antennas are durable under general military vibration conditions.

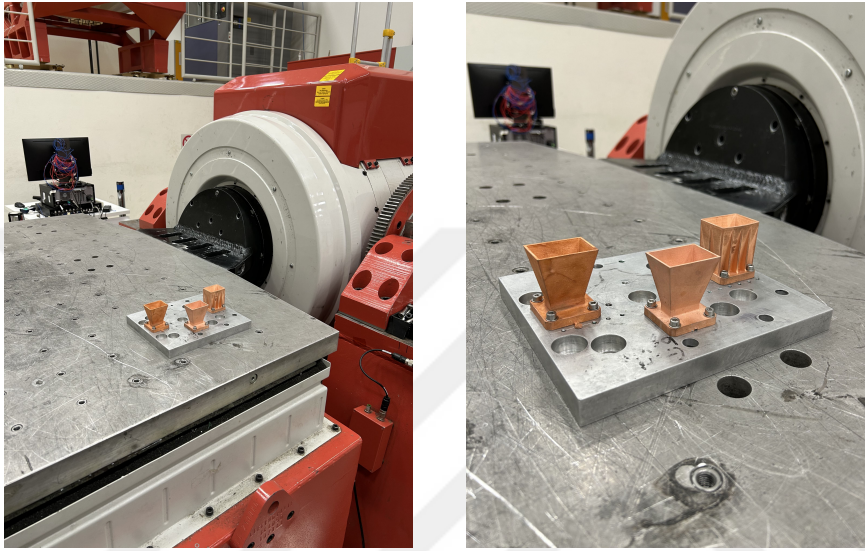


Figure 4.25: Testing setup for the vibration and shock tests

4.3.8 Test Method 516.8: Shock

The shock testing is designed to estimate the endurance of an item for non-repeating and infrequent shocks. These shocks may occur in the operation, handling, maintenance or transportation phase. With the test, it is possible to measure the fragility level of the material. Also, the results may direct the design of the packaging of the item. Generally, this test method is applied in order to clarify the effect of a sudden shock on the following matters [1]:

- The item may permanently deform as a result of high stress values.
- Material's dielectric strength, insulation resistance and magnetic and electrostatic field properties can alter.

- Electronic circuits inside the item may be damaged.
- Accelerated fatiguing may occur due to crack formation.
- The friction between the parts can increase or decrease, therefore the system may become malfunctioned.

There are 8 different shock test methods specified in the standard. These are Functional Shock, Transportation Shock, Fragility, Transit Drop, Crash Hazard Shock, Bench Handling, Pendulum Impact and Catapult Launch/Arrested Landing. Functional Shock is aimed to test the material in its functional mode. Therefore, the physical integrity, continuity, and functionality of the item are assessed. Transportation Shock is used to imitate the shock levels that may be encountered during transportation which can be considered repetitive shocks. A classical terminal peak saw-tooth shock profile is used in the test. The Fragility Test method is generally used in the design phase of the item in order to determine the fragility level of the material. Transit Drop is a drop test method and aims to imitate the accidental shock that may be encountered during the loading, unloading, mounting, etc. processes. Crash Hazard Shock Test is applied on the items that may harm the occupants and bystanders if the item is loose from the mounts or fail during a crash. Verification of the structural integrity of the item mounts, tie-downs or containment configuration during simulated crash conditions is the purpose of this procedure. The Bench Handling method is used to determine the ability of the test item to endure shock levels encountered during bench handling, bench maintenance and packaging. Lastly, Pendulum Impact is designed in order to test the ability of the test item (generally large shipping containers) to resist horizontal impacts.

In our case, the Transportation Shock test method will be used with $40g$ $11ms$ classical terminal peak sawtooth shock profile. The procedure is the following:

Step 1. Calibrate the shock machine.

Step 2. Remove the calibration load and fasten the test item with the test apparatus on the platform.

Step 3. Perform an operational test of the test item before exposure to a shock

wave.

Step 4. Subject the test item to the test pulse and record the necessary test data.

Step 6. For the classical trapezoidal shock waveform, repeat the previous steps for three axes in the positive and negative directions. This totals 6 shocks.

Step 7. Visually examine the item and perform a post-shock operational test of the test item.

For the test, the configuration seen in Figure 4.25 is used. The antennas are exposed to 6 shock pulses in 3 orthogonal axes as the standard specifies. Neither any deformation nor operational deficiency on the antennas is observed, therefore it can be concluded that all antennas are durable to $40\text{ g } 11\text{ ms}$ saw tooth shock profile.

4.3.9 Results

All tests that may be related to the antennas' life cycle are completed in the previous sections. Tests and their results are summarized in Table 4.2.

Table 4.2: The results from the antenna measurements and the military environmental condition tests.

	FFF	SLA	MFFF	CNC
Antenna Pattern	Pass	Pass	Pass	Pass
S₁₁ Parameter	Pass	Pass	Pass	Pass
High Temperature	Pass	Pass	Pass	Pass
Low Temperature	Fail	Fail	Pass	Pass
Temperature Shock	Pass	Pass	Pass	Pass
Humidity	Fail	Fail	Fail	Pass
Fungus	Pass	Pass	Pass	Pass
Salt Fog	Fail	Fail	Fail	Pass
Vibration	Pass	Pass	Pass	Pass
Shock	Pass	Pass	Pass	Pass

As previously discussed, all antennas are working properly on the intended bandwidth. The radiation pattern and S parameter measurements are convenient with the simulations. As for the military environmental condition tests, there are some deficiencies. All antennas were able to pass the high temperature, temperature shock, fungus, vibration and shock tests. But, the additively manufactured antennas couldn't pass the humidity and salt fog tests. Also, the FFF and SLA fabricated coupons failed in the low temperature tests, while the MFFF coupon wasn't affected by this condition.

The results and conclusions are further discussed in the following chapter and the improvements in order to pass the low temperature, humidity and salt fog tests are proposed as future works.



CHAPTER 5

CONCLUSIONS & FUTURE WORK

In this thesis, AM technologies for the fabrication of antennas are investigated. In the literature survey, it is realized that it is possible to manufacture antennas via AM technologies while there are numerous successful studies regarding the issue. It is also realized that there is a shortage of studies regarding the testing of the AM fabricated antennas especially in terms of environmental conditions. Thus, the focus of the study is determined as the fabrication of a horn antenna via AM technologies and testing the fabricated products by military environmental condition test standard, MIL-STD-810H.

For fabrication of the antennas, three different AM technologies are selected as FFF, SLA and Metal-FFF, which is a novel technology. The FFF and SLA fabricated antennas are electroplated with copper after 3D printing step. It is noticed that the coating surface quality is highly affected by the electroplating parameters. It is also noticed that the sintering stage is critical for the geometries with high aspect ratios such as thin & lengthy walls. Thus, design revisions were required for the MFFF fabrication. After the fabrications were completed, the features regarding the fabrication period were discussed.

The SLA antenna was the most accurate one among the other additively manufactured antennas in terms of dimensional accuracy. It was considerably close to the CNC manufactured product. The FFF antenna was moderate, and the MFFF antenna was the worst due to the sagging that occurred in the sintering stage. Therefore, CNC fabrication is the best candidate if the user is willing to achieve high accuracy.

The FFF antenna was the cheapest among all the antennas. Since the FFF type of

3D printers are the most popular and available type of 3D printers in the market, this result was expected. The cost of the SLA antenna was higher than the FFF but still, it was 65% cheaper than the CNC manufactured product. The MFFF antenna has an excessive cost owing to the high machinery, material and maintenance costs. As the technology becomes more available, these costs may reduce.

The surface roughness results were quite parallel to the dimensional accuracy results. High accuracy and lower surface roughness may be correlational considering the results. The SLA antenna was the smoothest antenna among the AM antennas, but the CNC antenna has lower roughness levels. This drawback may be one of the substantial shortcomings of AM compared to the conventional manufacturing approach.

The FFF and SLA antennas were the lightest antennas with quite similar weights. This is expected since they were fabricated out of polymers. The CNC antenna has moderate weight, but the MFFF antenna has an excessive weight. This is due to the copper being three times more dense than aluminum and also the support structures embedded into the geometry in order to prevent sagging.

In terms of strength, the aluminum antenna has the best yield strength with moderate elongation properties. The FFF and SLA antennas have the lowest strength and elongation properties. The MFFF antenna has moderate yield strength with superb ductility features. Thus, it is beneficial to avoid using the FFF and SLA fabricated antennas if high stress levels may be encountered during the life cycle of the antennas.

The SLA antenna has the lowest melting point temperature. This situation was also mentioned in the literature survey as a substantial drawback of the SLA technology. The FFF antenna has a moderate melting point temperature of 170°C. The metal antennas have considerably higher melting point temperature values which are quite unlikely to encounter during the antennas' life cycle.

The FFF and SLA antennas were fabricated within 16 hours including the coating process and compared to the conventional method, the results verified these fabrication methods being convenient for rapid prototyping purposes. While the CNC fabrication time is moderate, MFFF has a longer fabrication period. This is due to the washing and sintering stages, which take almost 3 days. Thus, it is advantageous to prefer the

FFF and SLA methods if an urgent fabrication is necessary.

Regarding the fabrication properties, SLA is the best candidate for relatively cheap, light, precise and fast fabrication with lower strength and ductility features. FFF is the cheapest method with moderate precision and low mechanical properties. CNC manufacturing is the best candidate for precision and mechanical strength but cost, delivery time and weight is relatively higher. MFFF generally has undesirable properties regarding accuracy, weight and fabrication time. But recalling it is a novel technology, these deficiencies are natural.

Regarding antenna radiation measurements, all the antennas performed sufficiently. The AM antennas were considerably similar to the CNC manufactured product both in antenna pattern and S parameter measurements. While the MFFF antenna delivered better maximum directivity levels, it performed slightly poorer in the S_{11} measurement. This situation refers that the dielectric and conductor losses are less in Metal-FFF. The SLA, FFF and CNC antennas were similar in terms of radiation properties and the results were compatible with the simulations.

In the military environmental condition tests, the AM antennas were durable to high temperature, temperature shock, fungus, vibration and shock tests. But, all AM antennas failed in humidity and salt fog tests which are essential tests of the standard. Additionally, the FFF and SLA fabrications had degradation levels in the low temperature test. This case is counted as a failure as the surface quality was not maintained thoroughly.

In brief, the conclusions of this thesis study are the following:

- AM offers viable options for antenna fabrication.
- The sintering stage is critical for the geometries with high aspect ratios such as thin & lengthy walls.
- The coating surface quality is highly affected by the electroplating parameters.
- Among the AM antennas, the SLA antenna was the most accurate antenna.
- Among the AM antennas, the FFF antenna was the cheapest antenna.

- The surface roughness results were parallel to the dimensional accuracy results.
- The FFF and SLA antennas were more preferable for rapid prototyping.
- In the MIL-STD-810H tests, all antennas were durable to high temperature, temperature shock, vibration and shock tests.
- It is seen that the antennas are not suitable to work in salty, highly humid and extremely cold environments.

Regarding future works, a substantial improvement may be adding a protective yet conductive layer to the additively manufactured antennas. Gold or silver coatings may be applied on the antennas for better performance in military environmental condition tests. Also, with silver coating, the antenna performance may be enhanced in terms of radio frequency due to higher conductivity levels than copper. These options are not covered in this thesis. Actual antennas may also be tested in all of the environmental tests rather than the test coupons. This case may be preferable since the effects of the tests may differ with the geometry of the test item.

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APPENDIX A

TECHNICAL DRAWINGS OF THE ANTENNAS

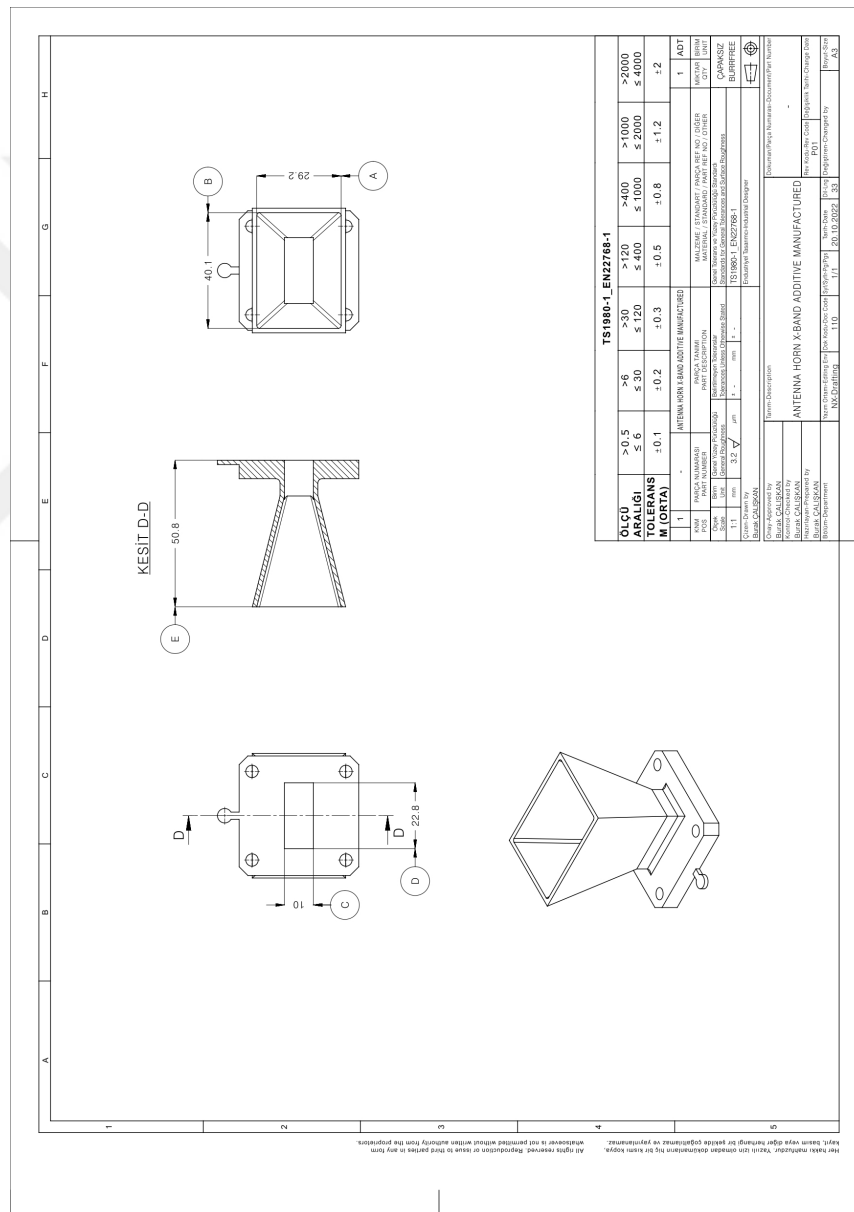


Figure A.1: Technical drawing of the critical dimensions of the antenna

PE9856B/SF-10 CAD Drawing
 WR-90 Standard Gain Horn Antenna Operating From 8.2 GHz to 12.4 GHz,
 10 dBi Nominal Gain, SMA Female Input Connector, ProLine

