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Návrh systému instalace uchycení a zakrytování antény na bezpilotní prostředky

Mounting and casing system for antenna for unmanned aerial vehicles

DIPLOMOVÁ PRÁCE

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Studijní program: N0716A270010 LETECTVÍ A KOSMONAUTIKA
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PODĚKOVÁNÍ

Ráda bych zde vyjádřila mé poděkování a vděčnost všem, kteří mi během mnoha měsíců pomáhali při rešerši, testování a psaní této diplomové práce.

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ANOTACE

Tato studie se zaměřuje na komplexní proces návrhu krytu pro dron s cílem optimalizovat celkovou funkčnost. Experimentální testy pomocí vlnovodů a analýzy nám pomohly vybrat vhodný materiál hodnocením propustnosti, odrazu a absorpčních schopností. Další výběr byl proveden pro anténu, která se v takovém dronu používá pro komunikaci, navigaci a přesné určování polohy. Konečná kombinace dobře navrženého krytu, pečlivě zvoleného materiálu a výrobní metody zvyšuje spolehlivost dronu.

ANNOTATION SHEET

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ANNOTATION

This study focuses on the comprehensive design process of a cover for a drone to optimize protection, performance, and overall functionality. Experimental tests through waveguides and analysis helped us to select suitable material by evaluating transmission, reflection, and absorption capabilities. Another selection is done for antenna that is used in such a drone for communication, navigation, and precise positioning. The final combination of a well-designed cover, carefully chosen material and manufacturing method enhances the drone’s reliability.

ABSTRAKT

Tato práce představuje komplexní studii návrhu krytu pro dron prostřednictvím rešerše o materiálech, anténách a krytech dronů, dále provedením mnoha experimentálních testů, analýzy výsledků, pečlivého výběru finálního materiálu a antény. Primárním cílem bylo identifikovat materiály, které by mohly nabídnout optimální vyrobitelnost, výkon z hlediska hustoty, odolnosti vůči povětrnostním vlivům a elektromagnetických vlastností. Vlnovody a vektorový síťový analyzátor byly použity pro experimentální část, kde byly měřeny různé vzorky odlišných tlouštěk, velikostí a materiálů, a hodnocena jejich schopnost odrážet, přenášet a absorbovat elektromagnetické vlny. PMMA vykazoval vynikající výsledky znamenající velmi dobré přenosové vlastnosti s minimální absorpcí a odrazem příchozích signálů.

Po testování byl proveden proces návrhu krytu, který zahrnoval poznatky získané z výzkumné části a z testů materiálů. Bylo představeno a diskutováno několik konstrukčních konceptů, přičemž hlavními kritérii byla snadnost výroby, aerodynamika, ochrana vnitřních součástí, rovnováha mezi lehkými vlastnostmi a funkčností.

Kromě toho byla volba antény jedním z klíčových prvků tohoto projektu, protože optimální příjem signálu je nezbytný pro provoz a efektivitu dronu.

Celkově jsme v této práci poskytli podrobnou diskusi o kritériích výběru, experimentální validaci, výběru materiálu a optimalizaci designu krytu pro dron a zároveň nabídli některé cenné poznatky pro budoucí studie a potenciální pokroky, které by mohly zlepšit drony.

ABSTRACT

This thesis presents a comprehensive study on design of a cover for a drone through the research about materials, antennas and drone covers, a series of experimental tests, analysis of the results, careful selection of final material and antenna. The primary goal was to identify materials that could offer optimal manufacturability, performance in terms of durability, density, and weather resistance, and electromagnetic properties. Waveguides and Vector Network Analyzer were utilized for the experimental part where tests with various specimens of different thickness, sizes and materials were measured and evaluated for their ability to reflect, transmit, and absorb electromagnetic waves. PMMA was demonstrating excelled results meaning very good transmission characteristics with minimal absorption and reflection of the incoming signals.

After the testing, the design process of the cover was carried out, incorporating insights gained from the research part and material testing. Multiple design concepts were presented and discussed while main criteria were ease of manufacturing, aerodynamics, protection of internal components, balance between lightweight properties and functionality.

Additionally, the choice of the antenna was one of the crucial elements in this project because optimal signal reception is essential for the drone’s operation and efficiency.

Overall, in this thesis, we provided a detailed discussion about the selection criteria, experimental validation, material selection, and design optimization of the cover for a drone while also offering some of the valuable insights for future studies and potential advancements that could enhance drone technology.

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LIST OF USED PROGRAMS

Autodesk Inventor 2022
Fusion 360
MatLab
Microsoft Office Excel
Microsoft Office World
VNA – Vector Network Analyser

LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

2DRMS – 2-dimensional RMS

3DP – 3D Printing

3G – The third generation mobile network

4G – The fourth generation mobile network

5G – The fifth generation (technology standard for cellular networks)

A – absorption

ABAS – Aircraft-Based Augmentation System

ABIA – Aircraft-Based Integrity Augmentation system

ABS – Acrylonitrile butadiene styrene

AM – additive manufacturing

BVLoS – Beyond-visual-line-of-sight flights

CAE – Computer-Aided Engineering

CEP – Circular Error Probable

CES – Consumer Electronic Show

CFD – Computational Fluid Dynamics

CFRP – Carbon fibre-reinforced polymers

CME – Coronal Mass Ejection

COTS – commercial off-the-shelf

CS – Commercial Service

csv – file format used in Excel or MatLab

D-Glass – Borosilicate glass

dat – MatLab file format

DGNSS – Differential GNSS

E1 – Spectral band (1559-1592 MHz)

E5 – Spectral band (1164-1215 MHz)

E6 – Spectral band (1260-1300 MHz)

ESC – Electronic Speed Controllers

EIA – Equatorial Ionization Anomaly

EMI – Electromagnetic interference

eMMC – embedded multimedia card

EPB – Equatorial Plasma Bubble

EU – European Union

FAA – Federal Aviation Administration

FEE – The Faculty of Electrical Engineering (at Czech Technical University in Prague)

FML – Fibre metal laminates

GBAS – Ground-based augmentation system

GFRP – Glass Fibre Reinforced Polymer

GLARE – Glass Fibre Reinforced Aluminium
GLONASS – Global Orbiting Navigation Satellite System
GNSS – Global Navigation Satellite Systems
GPS – Global Positioning System
HF – High frequency
IMU – Inertial measurement unit
IoT – Internet of Things
IPP – Ionospheric Pierce Point
ISMR – Ionospheric Scintillation Monitor Receivers
L1 – Signal with carrier frequency 1 575.42 MHz
L2 – Signal with carrier frequency 1 227.6 MHz
Lidar – Light Detection And Ranging
LTE – Long-term evolution technology
MEO – Medium Earth orbit
NAVSTAR – Navigation and satellite timing and ranging
OS – Open Service
PC – Polycarbonate
PETG – Polyethylene terephthalate glycol
PLA – Polylactide
PMMA – Polymethyl methacrylate
PMP – Polymethylpentene
PRS – Public Regulated Service
PUR – Polyurethane
QoS – Quality of Service
R – reflection
R95 – Radius 95%
RC – Radio Control
RMS – Root Mean Square
RNP – Required Navigation Performance
RPV – Remotely Piloted Vehicle
RTK – Real Time Kinematic
SAR – Search and rescue
SBAS – Space-Based Augmentation System
SE – Shielding efficiency
SS – Space Segment
svg – graphic file format
T – transmission
TCE – Thermal coefficient expansion
TEC – Total Electron Content

UAV – Unmanned Aerial Vehicle
UE – User Equipment
US – User Segment
USB – Universal Serial Bus
uSSD – Unstructured Supplementary Service Data
VHF – Very high frequency
VNA – Vector Network Analyzer
XLS – Excel file format

Elements

Ni – Nickel
Al – Aluminium

Units

µm – micrometre
dB – decibel
dBi – dB(isotropic) – antenna measurement: the gain of one antenna compared with the gain of a theoretical isotropic antenna
dBm – milliwatt
g – gram
GHz – Giga Hertz
GPa – Giga Pascal
Hz – Hertz
km – kilometre
MHz – Mega Hertz
Mm – millimetre
MPa – Mega Pascal
mW – milliwatt
ppm/°C – parts per million per degree Celsius
V – Volt
Z – Impedance

Denoted characteristics and properties

$\tan\delta$ – dielectric loss tangent
ε_r – relative permittivity
$\delta\varepsilon_r$ – the change in relative permittivity
μ_r – permeability
A – absorption
R – reflection

T – transmission

S11 – Input Reflection Coefficient

S12 – Reverse Transmission Coefficient

S21 – Forward Transmission Coefficient

S22 – Output Reflection Coefficient

SE – Shielding efficiency

1. Introduction

Unmanned aerial vehicles (UAVs), also known as drones, have become ubiquitous across various and numerous industries due to their adaptability and versatility and exponential rise in popularity. From construction and emergency response to agriculture and surveillance - applications across a wide array of industries, drones are revolutionizing operations and traditional workflow with their ability to conduct inspections, collect aerial data, and perform tasks in challenging environments. However, to fully harness their potential and open new possibilities for innovation, communication capabilities and precise navigation are essential. This can be mediated by Global Navigation Satellite Systems (GNSS) as they play a pivotal role in enabling those capabilities. By leveraging satellite signals, drones can achieve high accuracy in their operations and movements e.g., centimetre-level accuracy, facilitating tasks such as autonomous flight, aerial mapping, and surveying. Advanced techniques such as DGNSS (Differential GNSS) and RTK (Real-Time Kinematic) further enhance the reliability and accuracy of navigation systems. Furthermore, modern communication systems, long-range communication protocols, 4G and/or 5G networks facilitate seamless data exchange between drones and other devices, allowing drones to operate in complex environments.

The necessity of material selection for drone cover and designing this cover are two critical aspects of development of robust drone as the cover not only adequately protects the internal components from external environmental factors such as moisture, dust, and impact during crash (i.e. with a tree branch), it also plays a significant role in minimizing electromagnetic interference and ensuring optimal signal propagation. The choice of material must balance several requirements such as light-weight characteristics, durability, and signal transmission properties. Testing could help in identifying list of materials that are capable to meet these requirements and ensure that the performance of the drone will not be compromised.

Currently, there is a limited understanding of how different materials affect communication efficiency and signal propagation when utilized in parts of drones e.g., top, and bottom covers. This gap in knowledge leads to suboptimal material choices in some companies and industries which leads to affecting the overall performance of UAVs. Addressing this issue is crucial and it is one of the reasons why this research aims to solve the problem of identifying suitable materials through testing and the following analysis.

The primary goal of this thesis is to do the research in terms of existing utilized materials, identify the most suitable materials for drone covers and propose design idea that could protect the internal parts and electronics of the selected drone. The specific objectives include: Research about different drones and their covers to analyse what are the trends in real-world scenarios and find some inspiration for proposing our own design of the drone cover. A comprehensive material research to evaluate different characteristics. Conduct tests to evaluate impact of different material on signal transmission and / or reflection. After finalising cover design, try to select manufacturing method of it.

The hypotheses, that we work with in this project, are: Certain materials will exhibit signal attenuation – we talk about materials that are already utilized for drone cover by some companies. For instance, many companies use carbon or carbon fibre composites, because they present balance between weight, durability, and easy manufacturing method. But these materials are more likely to weaken the coming signals. We should also think about other materials that can reflect the signal or cause interference of signals from satellite and signals from electronic components in the drone.

Through this project, the goal is to contribute insights into materials and their selection and facilitate to develop the cover which will allow more reliable and efficient positioning and communication of drones.

2. State of the art research

The research part delves into the critical aspects of drone technology, focusing on material selection, design of the drone cover, antenna technology, and communication systems with satellite systems. Comprehensive examination aims to provide understanding of how each element enhance or worsens performance and functionality of UAV.

One of the primary reasons for discussing utilization of GNSS in the context of UAVs and drone technology is their significant role in providing accurate location data in positioning and facilitate meticulous precision with real-time information. This allows drones to autonomously fly on predefined routes, execute complex flight patterns, and perform systematic area coverage while minimizing the risk of human error and executing more efficient utilization.

One of the sections will explore the benefits and challenges of different communication systems. These systems include integration of mobile networks such as 4G and 5G networks into drones. And one of our goals is to examine what frequencies utilized networks work at to select frequencies that are important to analyse during the testing process part of this diploma thesis.

The next part of the text will explore antenna technology, what are various types of antennas, and evaluate their performance characteristics and suitability for drone applications. The selection of appropriate antenna is crucial, and we need to think not only about its placement, but also e.g. how we can integrate it with other electronic components that are internal part of every UAV.

Materials selection is another fundamental aspect of cover design, and this research will investigate a range of materials. Also, some of previous studies and results of testing will be reviewed to gain comprehensive understanding on electromagnetic characteristics, and other properties including the mechanical ones. The goal of this section is to identify materials that we could use for testing in practical part of this thesis.

The cover is not merely an aesthetically looking element on the drone, but we cannot forget it is an important component that can enhance aerodynamics characteristics of whole drone, and mainly shields internal systems from several factors including environmental ones e.g., moisture, dust, rain etc. So, the final objective of this research includes assessing the design variations and design proposals utilized by other companies and hobbyists.

2.1. GNSS

The development of satellite navigation began in 1957 resulting in the US Navy Transit GNSS - Global Navigation Satellite System that became operational in the mid-1960s. The achieved navigation accuracy was in the order of 200 meters. When we move to the present time, in the new world with technological revolutions, GNSS is fast becoming a key instrument and indispensable technology in terms of satellite-based navigation systems which allows measuring position in real time with high accuracy on the Earth and provides global availability of signals. GNSS has opened the wide door for the implementation of navigation and positioning in various scientific, military, and even civilian purposes. Different Global Navigation Satellite System technologies evolving from Global Positioning System (GPS) to Quasi-Zenith Satellite System and its applications has been looked at as the market opportunity since it is able to operate as per user needs and requirements. [2]

GNSS satellites are placed in mid-Earth orbit at an altitude of about 20,000 km and its structural organization is an aggregate of three segments: Space Segment (SS), Control Segment (CS) and User Segment (US). SS is made up of a constellation of 24 satellites for GPS and GLONASS and 32 satellites for BeiDou and Galileo. CS consists of stations on different places on Earth and they are monitoring and maintaining the GNSS satellites. User Segment provides receivers. They are the ones who process the navigation signals traveling from the GNSS satellites and then their purpose continues while they calculate position and time. [2]

The functional organization of GNSS is based on systems and concepts of great significance. These include time systems, coordinate systems, accuracy improvement systems, factors affecting accuracy and the concept of pseudo range, while the positioning principle is established on the coding algorithms, the signal structure, and the principle of frequency separation. [2]

Currently, there are several global navigation satellite systems e.g., GLONASS, GPS, and Galileo, in various stages of operation and they are designed to provide accurate navigation, positioning, and timing services worldwide. [32] While they share the same fundamental purpose, each system has unique characteristics. What are their differences?

2.1.1. GPS

The GPS (Global Positioning System) is developed and operated by the US Department of Defence under its NAVSTAR satellite program. It consists of a constellation of thirty-one active satellites with additional operational spares, in six operational planes, orbiting the Earth in a MEO (medium Earth orbit). Four or more GPS satellites will always be visible from any point on the surface of the Earth. The legacy GPS satellite transmits two L-band spread spectrum navigation signals on an L1 signal with carrier frequency 1575.42 MHz and an L2 signal with 1227.6 MHz. [32]

Compensating for ionosphere propagation delays: For estimating the distance between the user and the satellite, the time it takes for a navigation signal to travel from transmission to reception is important. Atmospheric conditions, particularly the ionosphere, is influencing the signal propagation delay and as the signal traverses the ionosphere, the delay varies with the frequency. To mitigate this issue, two carrier signals are utilized. [32]

2.1.2. GLONASS

The Global Orbiting Navigation Satellite System (GLONASS) is a secondary system for global positioning placed in orbit by the former Soviet Union and now operated by Russia. It has 24 satellites, distributed in 3 orbital planes of 8 satellites each. This satellite transmits the legacy GLONASS two navigation signals in the L1 frequency band with frequency between 1598 - 1605 MHz, and in the L2 frequency band with frequency between 1242 - 1248 MHz. The modernized version, the first of next-generation GLONASS-K satellites, was launched in February 2011. Some signals are transmitted at a frequency of 1202 MHz, others at L1 and L2 bands. [32]

2.1.3. Galileo

The Galileo system with a 30-satellite constellation is under development by the European Union (EU) that intends the system to provide various levels of services. It operates in the L-band and in three spectral bands E6 (1260-1300 MHz), E5 (1164-1215 MHz), and E1 (1559-1592 MHz) with MEO satellites that operate in three orbital planes. The Open service (OS) can be utilized for positioning and timing, it is accessible to any user equipped with a suitable receiver and is free of direct user charge. Then there is Commercial service (CS) that offers performance higher than the previous one. The Public regulated service (PRS) is an access-controlled service utilized by government-authorized applications e.g., for coast guards and police. The Search and rescue (SAR) service should contribute to the international cooperative effort. [32]

Table 1: Properties of different most well-known GNSS [33]

GNSS	Number of satellites	Altitude [km]	Frequencies [MHz]
GPS	32 (+3)	20 185	1575.42, 1227.6
GLONASS	22 (+4)	19 100	1597 - 1606, 1238 - 1250
Galileo	0 (+1)	23 222	1575.42, 1278.75, 1191.795
BeiDou	13	21 500	1610 - 1626.5, 2483.5 – 2500

2.1.4. Factors affecting GNSS performance

GNSS uses satellites to broadcast time and location by utilizing synchronized atomic clocks and at the same time, the time of clock is corrected by the true time of the ground clock. For instance, clocks of GPS receivers are less stable, because they are not synchronized with the true time. GPS receivers are able to get signals of multiple satellites and they can calculate the exact position while the accuracy is in meters. The different factors play a role in the GPS observations: satellite related factor (satellite clock error, orbital error), propagation errors (multipath error, the tropospheric refraction error, the ionospheric delay error), the receiver error (observation error, the receiver clock error). Using GPS for position estimation by utilizing a GPS receiver, a barometer and an IMU (Inertial measurement unit), more than 4 satellites have to be detected, otherwise localization would fail. [1]

GNSS applications require secure information to control positioning and drive drones, vehicles and so on. A key issue during the utilization of GNSS positioning and navigation is vulnerability to spoofing, jamming, and meaconing, whereas spoofing is the most difficult type of attack. [2, 15]

Other important factors that are affecting the resulting performance of GNSS in applications are antenna design, its placement and orientation in the vehicle or other application, and interference with other equipment, its accuracy and reliability and integration complexity including compatibility with existing hardware and software systems and communication protocols. We will talk about these factors later in the chapter about antennas.

Lastly, the environmental factors such as weather, terrain and electromagnetic interference from nearby structures affect signal reception and signal obstruction - topics that we will discuss in later subsection.

2.1.5. Ionospheric scintillations

Before proceeding to examine the accuracy of GNSS receiver and explaining how it is affected by surrounding environment and other effects, it is important to highlight the contribution of the ionosphere ionized by solar radiation as signals from GNSS satellite travel across this upper region of the Earth's atmosphere and a propagation delay plays a pivotal role. The delay is commensurate with the frequency of the radio signal and the total electron content (TEC). The second number is the total number of free electrons which is very variable with location and time and represents an appropriate indicator of ionosphere conditions. These are the electrons which the signal encounters along the ray path while traveling from the satellite to the receiver. [2]

An additional effect on signals is located particularly on high and low latitudes. We are talking about the presence of ionosphere plasma irregularities which induce changes in amplitude at a fast pace and ionosphere scintillations that can broadly be defined as phase of the received signals. Previous studies mostly defined these rapid fluctuations of the signal as a reason for the system performance degradation. In contrast, this also provides and emphasizes significant information about ionospheric irregularities of different scales. The total electron content is estimated with the help of electron density profiles obtained using radio occultation of signals. [2]

Prominent challenges and concerns to technological applications are known to be associated with fluctuations in amplitude and/or phase when GNSS signals travel the ionospheric layer. Ionospheric scintillation is coming from the sudden and unexpected variations in the ionospheric index of refraction linked with the equatorial plasma bubbles (EPBs). Networks of Ionospheric Scintillation Monitor Receivers (ISMR) deployed for example in the South American region monitor the climatology of scintillations and the dynamics of equatorial plasma bubbles impelling scintillations. Equatorial plasma bubbles are structures in ionosphere symmetrically aligned along geomagnetic equator so-called also dip equator. [2, 7]

Figure 1 reveals that there has been a fluctuation in values of Total Electron Content (TEC) over different times of the day while measured over one country – Brazil during November 16th, 2014, with the indicated dip equator and three GNSS ground stations. [7] Equatorial Plasma Bubbles and Equatorial Ionization Anomaly (EIA) region, highlighted in the figure, happen because of the space weather as it has an effect on ionospheric phenomena. [7, 16] More information about these events is presented in chapter 2.1.10. about Space weather, where we refer to Mamoru Ishii's (2024) comprehensive study reporting on this matter and analysis about space weather impact on navigation.

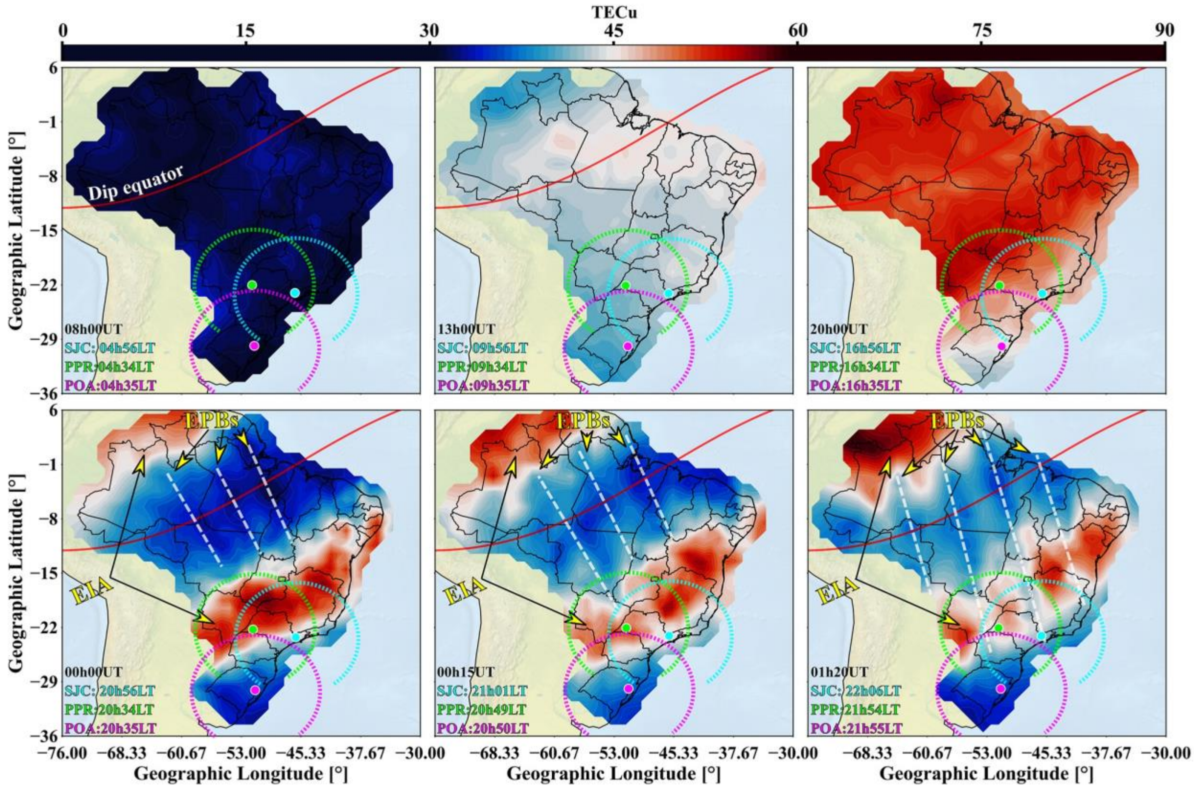

Figure 1: TEC values with highlighted EIA region and EPBs [7]

Figure 2 presents the alignment condition between the received signals elevation and azimuth angles. It also analyses how signals project onto the geomagnetic declination and inclination angles at the Ionospheric Pierce Point (IPP) altitude – that is generally assumed at 350 km above the Earth's surface. [7]

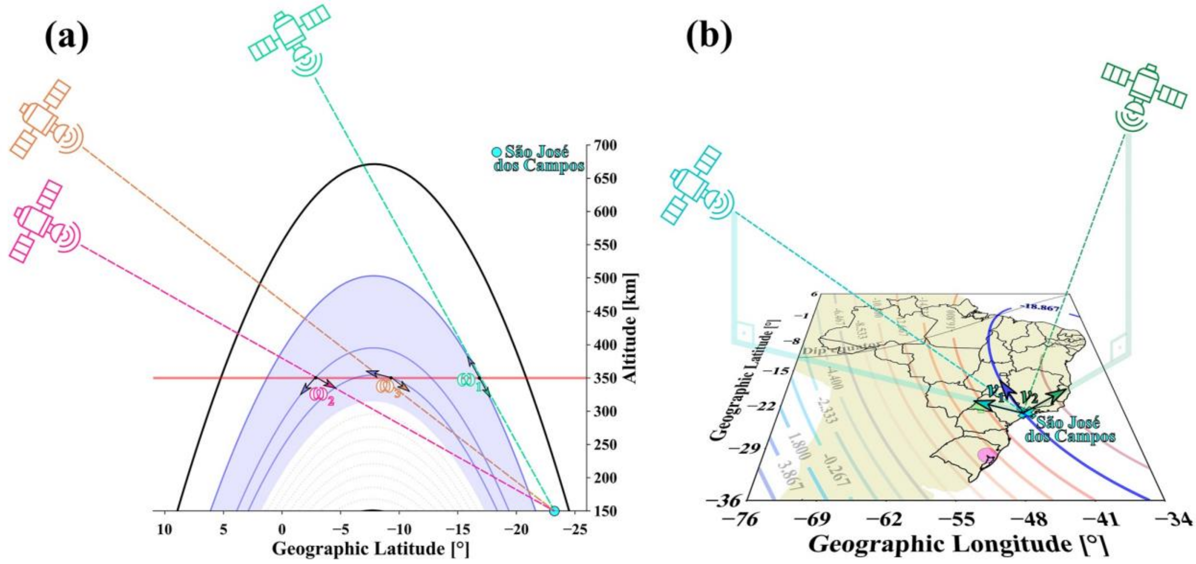

Figure 2: The alignment condition between the received signals elevation and azimuth angles [7]

2.1.6. Security of GNSS

Let's introduce, very shortly, a few problems affecting the security of GNSS. This is a very wide topic, and it would intervene in the issue of this topic only in case we want to use the cover of the drone to block out the signal coming from the devices on Earth - which is not the goal of our project.

Several factors contribute to data degradation:

- Fading, which reduces carrier-to-noise ratios $\left(\frac{C}{N_0}\right)$,
- Multipath effects causing reduced $\frac{C}{N_0}$ and errors in range/phase,
- Doppler shift affecting signal tracking,
- Jamming, meaconing, spoofing and interference,
- Antenna obstruction, such as interference from wings during manoeuvres. [11, 15, 34]

Accuracy of GNSS relies on quality observable measurements, which are prone to errors across space, control, and user segments. A significant source of GNSS error is multipath, it distorts the signal phase. Multipath is challenging to model and eliminate and it depends on factors such as antenna type, receiver environment, and tracking algorithms. For instance, to address these challenges, the system ABIA (Aircraft-Based Integrity Augmentation system) that continuously monitors GNSS integrity was developed for aviation. The system alerts the Automatic Flight Control System when integrity thresholds are violated. [11, 14]

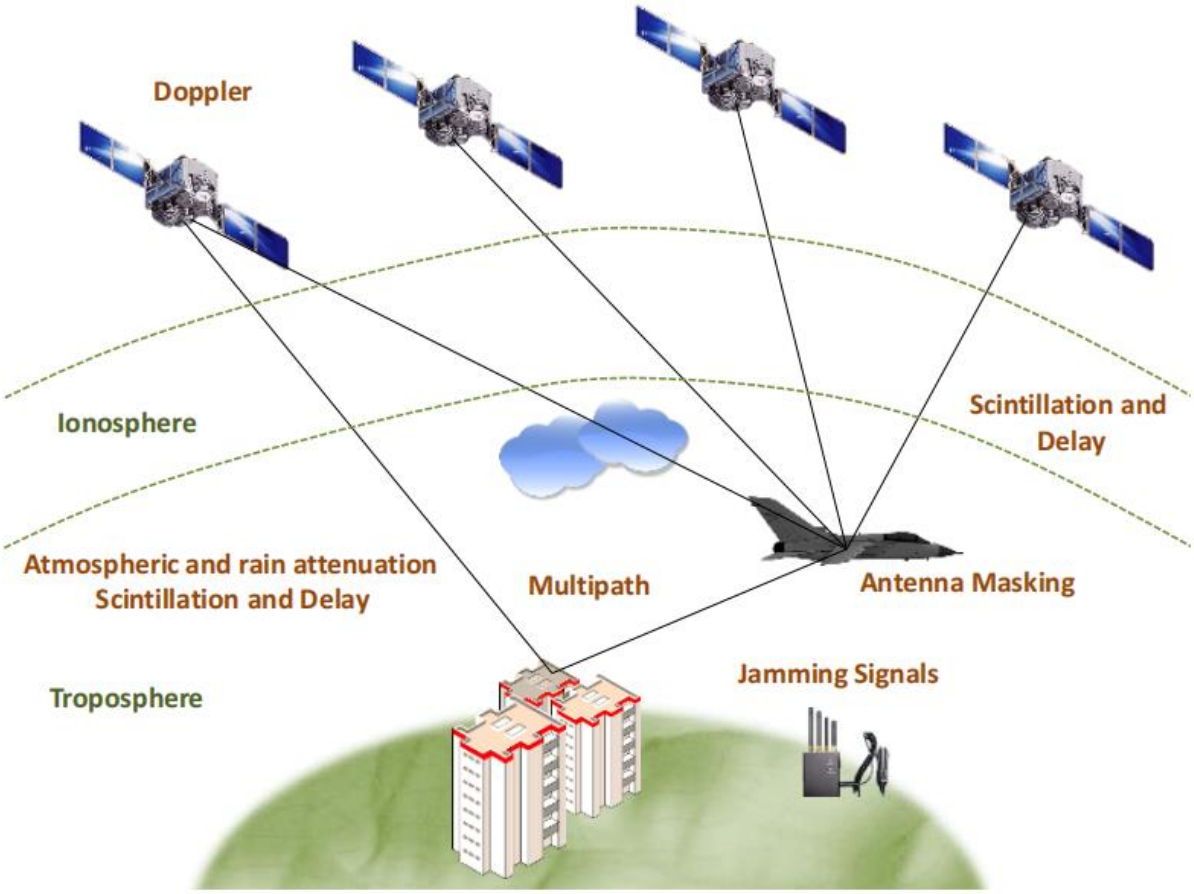

Figure 3: Source of GNSS signal degradations and outages [11]

2.1.7. Multipath errors and mitigation techniques

Multipath errors occur in GNSS-based navigation systems in the moment when signals from satellites are reflected off nearby surfaces, such as bodies of water, buildings and terrain features and reach the receiver antenna. Reflected signals are combined with the direct signals and together, they result in signal interference at the receiver. The combined signals are then interpreted as the direct signals by the receiver, and this leads to errors in position estimation. Multipath errors can distort the signal phase and function. This creates a challenging situation to accurately determine the receiver's position. [32] This problem is more important than other types of the errors because using the cover on the drone can affect the alternative signal path much more than the main direct signal.

Several strategies and techniques can help mitigate multipath errors in receivers. These include e.g. antenna location strategy (including placement optimization e.g., mounting the antenna on a high point of the drone), antenna design (using antennas with features such as ground planes) and differential techniques, such as Real-Time Kinematic can help correct for multipath errors by comparing signals received by the drone with the ones from a reference station. [32]

2.1.8. Ground-Based Augmentation System

Several strategies enhance Required Navigation Performance (RNP), including Ground-based augmentation system (GBAS), Space-Based Augmentation System (SBAS), and Aircraft-Based Augmentation System (ABAS) all aimed at improving availability, accuracy, integrity, and continuity. Together they create a space-ground-avionics augmentation network. [11]

GBAS is a system that enhances the performance of GNSS-based navigation systems and improves the accuracy, and availability of positioning information by providing correction signals. Dual-frequency GNSS receiver in the drone, capable of receiving signals from multiple frequencies and constellations allows for better mitigation of multipath and ionospheric errors. [32]

Precision position services provided by GBAS is limited and utilized in approach phase only, while SBAS (mentioned in the following subchapter) is capable to provide precision position services in all flight phases, while its accuracy is superseded in approach phase by that of GBAS system performance. [11] Meaning that for the drone, it is more suitable to use SBAS.

2.1.9. Space-Based Augmentation System

SBAS is a system that enhances the integrity, availability, and accuracy of GNSS signals. It augments the existing signals from satellite constellations with additional integrity monitoring capabilities and correction data. [11, 32] In comparison, SBAS offers precise positioning throughout all flight phases, but GBAS outperforms it in approach accuracy. [11] For our project, SBAS is more important as the drone will use it more likely to improve reliability, extend coverage area of GNSS signals and enhance positioning accuracy.

2.1.10. Space weather and how does it affect signal propagation

Several questions were asked during the time of working on this project. For instance, how does space weather affect signal propagation? Can space weather affect satellite terminals, such as the ones utilized for Starlink, when we want to use the signal to control the drone? And how?

Space weather is well known for its potential to disturb modern navigation and communication systems. Solar energetic particles, solar flares, and coronal mass ejections (CMEs) have the potential to induce ionospheric disturbances that disturb L-band signals utilized in satellite-based positioning, but also HF (high frequency), VHF (very high frequency) in radio communication. For instance, intense ionospheric disturbances can worsen or block access to satellite-based positioning, timing, and navigation services crucial not only for infrastructure operations, but also for other applications. Therefore, it is paramount to mitigate the adverse effects of space weather and devise protective measures. Space weather and the current situation of the solar cycle and its effects trigger various ionospheric and other phenomena. These include Equatorial Plasma Bubbles, auroral precipitation, and polar cap absorption. [16]

Sun is the primary radiation source for ionosphere and solar activity significantly influences the estimation of ionospheric electron density. In order to interpret solar activity, various solar weather indices are employed e.g., solar radio flux, sunspot number, geomagnetic K_p index (the level of geomagnetic activity). [33]

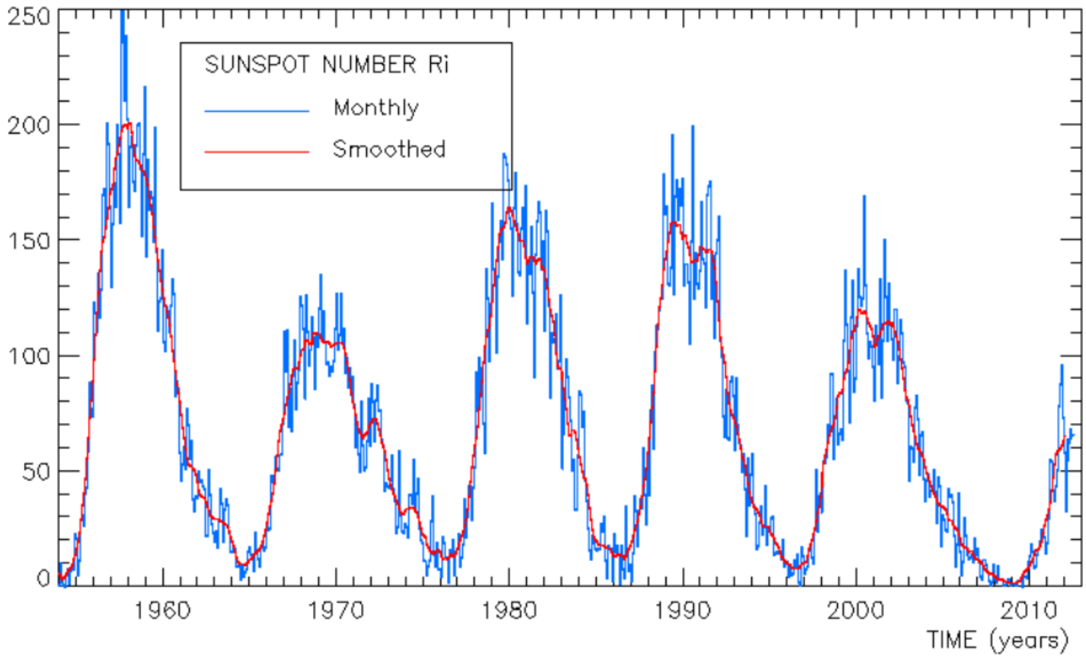

Figure 4: The monthly sunspot number for 5 solar cycles [33]

From the figure above we can see that the Schwabe cycle also known as the solar cycle is a nearly periodic 11-year change in the Sun's activity. During the whole cycle, there are variations in the number and size of observed sunspots, fluctuation of solar flares and levels of solar radiation. This specific figure presents the monthly sunspot number in the blue line for years 1950s to 2010s. The red line shows monthly smoothed values. [33] We can use the graph to calculate the prediction of the beginning and end of the next solar cycles. And in the near future, talking about the end of the year 2024 and the beginning 2026, it is expected that the maximum of the solar cycle will occur.

The solar maximum phase leads to higher levels of solar radiation and geomagnetic disturbances that can impact the Earth's ionosphere and cause ionospheric irregularities and fluctuation in electron density. [16, 33] As we already know from previous reading, the ionospheric disturbances can introduce errors in the signal propagation. This leads to

Table 2: Ionospheric phenomena and how they affect communication [16]

Phenomena	Affecting area	Affecting duration	Affected Ionospheric region	Affecting utilities
Short Wave Blackout from solar flare	Dayside of the Earth, maximum around equator region	Several min – several hours	D region	HF, VHF, LF, VLF
Short Wave Blackout from REP events	Mid latitudes	Several min - several hours	D region	HF, LF, VLF
Solar Radio Burst	Dayside of the Earth, maximum around equator region	Several min – several hours	–	Various
Polar Cap Absorption	High Latitude Region	Several min – several days	D region	HF
Auroral disturbances	Auroral Oval	Several hours	D and E region	HF, GNSS
Ionospheric positive storm	Global	Several hours	F region	GNSS
Ionospheric negative storm	Global	Several hours	F region	HF
TIDs	Global	Several hours	F region	GNSS, VHF
EPBs	Local post-sunset and nighttime of equatorial and mid-latitude region	Several hours after local sunset	F region	GNSS
Es layer	Dayside of the Earth	Several min - hours	Es	HF, VHF
Polar patches	Polar regions	Several hours	F region	HF, GNSS, satcom

ionospheric delay and scintillation effects. And finally, all this can affect the reliability and accuracy of positioning and navigation systems, including those for drones. This is another reason why it is important to create the cover for the drone that will disturb the coming signal as little as possible since there are all other ways the signal can be disturbed before getting to Earth's surface.

2.1.11. GNSS opportunity in market

Due to its design and functioning, GNSS has long been a question of great interest in a wide range of fields. These include geodetic and cartographic applications and precision agriculture where use of GNSS can play an important role in addressing issues and provide new insights into mapping of the fields, crop scouting, planning, sampling of soil, monitoring, harvesting of yield over a large spatial coverage. While it also allows farmers and workers to use the technology in rain, dust, fog, and even in low visibility for the activities which require accurate positional information in order to reduce time of completion and optimize the operational costs. [2]

Defining a sophisticated mission for drones is not an easy task. There have already been efforts to come up with a list that would be a part of classification schemes, but these lists tend to become out of date very fast as new concepts and missions constantly arise. Civilian and military are two major divisions of UAVs' missions, but there is also significant overlap between these areas. E.g., in the military the mission can be called surveillance, and it will be observation in a civilian application. [10]

2.2. Communication

Real-time flight control, mission control or even real-time access to the drone data allowed by reliable wireless communication e.g., the cellular network as a promising candidate is a key enabler for UAV applications. [31]

The impact of various parameters, such as drone altitude, antenna tilt and performance indicators, such as throughput, coverage probability and spectral efficiency, and also, utilization of the same cellular infrastructure, spectrum and the coexistence of aerial and ground users should be investigated. The interference is important to properly dimension the antenna parameters and network parameters because it is significant to aerial users. So, when the antenna and network parameters are sufficiently optimized, the communication and network achieve more efficient overall area spectral efficiency. [31]

For most of the novel applications and roles of drone’s real-time data exchange is significant and mandatory as those applications are dependent on reliable control. The technology serves two main purposes: data communication, and command and control services. The following key features are associated with those two services:

- To guarantee reliable tracking of drones (autonomous or human-driven) and control, the continuous connectivity and high coverage are necessary.
- To enable real-time applications (e.g., event monitoring) and robust remote control, low latency is essential. [31]

Additionally, if the application heavily relies on data exchange, the following capabilities may be necessary for technology:

- Secure communication - needed for privacy and data protection,
- Licensed spectrum - fundamental for mission-critical applications,
- High throughput - allowing video monitoring and data exchange,
- System scalability - supports fast growth of drones,
- Location verification - crucial for traffic management,
- Regulatory compliance of drones’ communication. [31]

Integrating drones into the LTE (long-term evolution technology/systems) is not a simple procedure as this technology is designed for serving ground users. There is a high possibility that some designs might not be suitable for drones e.g., some BSs (base stations) tilt antennas down to point towards the ground, but if this method would be used in aerial devices, it would induce a gain loss of antenna. The other consideration is that inter-cell interference assumptions and spatial reuse factors optimized for ground propagation conditions are not capable of fitting the needs of drones. [31]

It is crucial to recognize potential conflicts between aerial and ground user equipment (UE) and also, consider various design factors and their effects on the quality of service (QoS) of those two communities of users. Thoughtful characterization of the properties of ground-to-drone links and the relationship with the main network parameters is required. [31]

2.2.1. 4G

Incorporating a mobile network into the drone offers numerous benefits as it enhances control and command capabilities but also it is contingent upon sufficient network coverage in the area. Having a mobile network on the drone facilitates control beyond line of sight and enhances safety with real-time information and data transmission to the drone traffic management system. Various types of mobile networks include 3G, 4G (LTE), and currently also 5G networks, and they can be integrated into the drone. [29] Each technology is unique, follows a different standard and they vary in implementation and operation.

UAVs need to ensure reliable, safe, and efficient flight operation. And depending on their mission, they may need to receive and/or transmit mission-related data such as data packets for relaying from/to ground entities, aerial images, etc. Mobile network 4G and 5G - they provide high-speed data transmission, allowing for more responsive and faster control of the quadcopter. Additionally, they offer improved coverage and reliability compared to traditional communication methods such as radio control. One of the key advantages of utilizing 4G and 5G technology is the ability to access a larger network infrastructure. This allows the drone to operate over longer distances and in more remote areas which is beneficial for applications such as monitoring of large areas (e.g., of fields in agriculture), participate in rescue operations and delivery services.

- Advantages: cost-effective, almost ubiquitous accessibility and superior performance
- Disadvantages: potential interference with terrestrial communication, unavailable in remote areas. In some scenarios and remote areas such as desert, forest and sea, the cellular services are unavailable for UAV communication despite their promising advantages.
- Smartphone - can be used as an alternative option if the drone is capable of connecting to the 3G/LTE mobile network. [29, 30, 31]

2.2.2. 5G

What does the integration of drones and 5G networks look like and what are the unsolved related issues? Due to the high level of interference, integration of drones into future networks might be challenging. This could be mitigated by choosing optimized antenna beamwidth and low flying altitude. A fruitful area for further work may include the topics in the following sections.

2.2.2.1. Handover procedures for cellular-connected drones

Handover procedures differ from those for ground-based users. The drone can detect multiple line-of-sight base stations radiating signals through the antenna's side or main lobe resulting in the different cell pattern. Handover characteristics for aerial users are led to vary as they are influenced by different factors such as altitude, mobility patterns of the drones and blockage distribution. [31]

2.2.2.2. Communications utilizing millimetre-wave (mmWave) technology

Communications utilizing mmWave technology holds particular promise for drones and can extend application of 5G and future networks to drone communications due to line-of-sight communication characteristics. However, in order to be able to utilize mmWave for drones' communication effectively, it is important to properly address challenges caused by drone movement. These challenges are rapid beamforming training and tracking, signal blockages, and mitigating Doppler effects.

- In terms of higher frequencies and longer links, it is important to address the impact of the atmosphere. Influence from both blockage and atmospheric effects depend on the height above ground level and on the physical environment.
- Atmospheric influences are more significant for aerial vehicles than for ground-based applications. Due to them, mmWave transmissions encounter additional atmospheric attenuation outside of the typical free-space path loss. Frequency-dependent attenuation, together with attenuation generally increasing with higher frequencies (lower wavelengths) / both of them arise from 3 main sources and is also a crucial factor in maintaining communication links. The first source is suspended liquid particles e.g., cloud or fog. The second one is gaseous molecular absorption. mmWave signals interact with those molecules. And the last one is caused by precipitation e.g., rain.
- High-Capacity Cellular Networks and drone use cases:
  - Drones present a multitude of applications, and they can serve very well as a viable solution to address critical challenges. For instance, during temporary events, they can function as dynamic hotspots, and additionally, during natural disasters or in situations where it is necessary to provide assistance during network downtime, drones can help bridge coverage gaps. The fundamental advantages of mmWave communication, including high bandwidth (that can provide high data rates) and narrow beams (useful to reduce interference), are beneficial for all these applications even though there are some key challenges such as sensitivity to blockage.

- Blockages play a crucial role in mmWave communication systems. The impact of environmental factors varies depending on the relative position and the scenario, but blockages primarily arise from mobile objects (e.g., vehicles) and from fixed objects such as foliages, buildings, street fixtures and they apply to both interference links and signal transmission. [31]

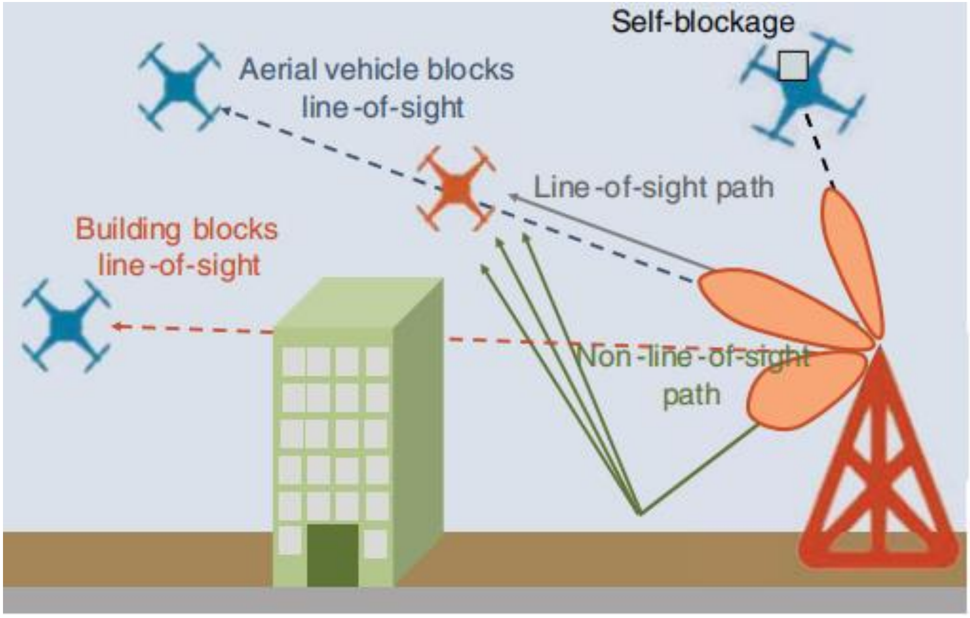

Figure 5: Different scenarios of blocking signal in a mmWave communication systems for aerial applications [31]

2.2.3. Communication system

Recent developments and trends have led to a proliferation of studies that offer the use of GNSS to control spatial coordinates of drones and have heightened the need for utilization and integration of 5G together with GNSS to achieve cooperative and ubiquitous positioning. Their combination is important in critical environments and usually, 5G is a supplement when GNSS is unavailable, but also the 5G network can help reduce the operation delay and secure the operation error within a few centimetres. [4, 5]

Figure 6 presents the correlations among the three monitoring of position obtained from the research Zhang et al. in [4]. It can be seen from the figure that the position obtained only with GNSS (black line), the position calculated with an algorithm utilizing data from both, the GNSS and 5G (red line), and the position of a moving object at a fixed linear velocity and angular velocity (blue line) is compared. This image is quite revealing, and the most striking result is that the presented red line nearly coincides with the blue one. This means that the algorithm is effective and the error in the results is small. [4]

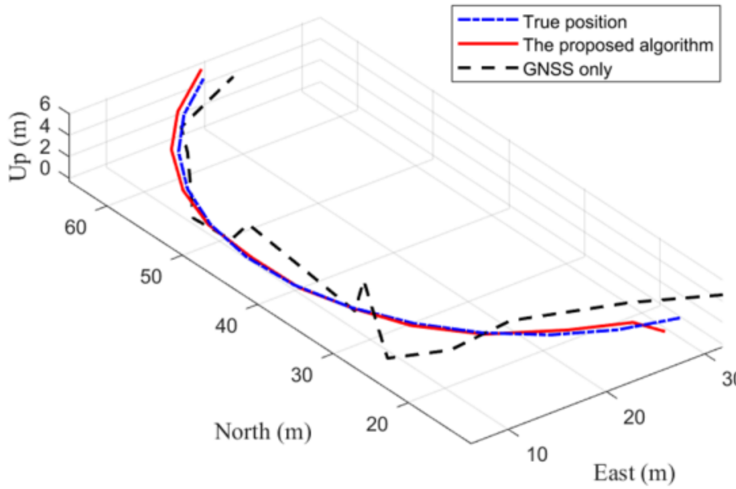

Figure 6: Positioning results and comparison with moving object [4]

2.3. Materials

In the realm of UAVs, the choice of materials plays essential role in determining the performance of drones as it directly influences the propagation of signals from satellites and it either reflect them or transmit them through the cover of the drone. This chapter will examine various materials that are already utilized in some drone constructions, review previous studies, and additionally, it also explores other materials that are consider as a good candidate for cover.

2.3.1. Commonly utilized materials

The material selection process plays a critical role. Lightweight materials reduce the cover's weight and have a potential to enhance drones' performance. Among the array of available materials, including PLA, ABS, metal alloys, nylon and others, this study focuses on materials chosen for their suitability for manufacturing e.g., for additive manufacturing (AM) and forming. [39] A wide variety of materials employed specifically in UAVs for structural components can be reinforced composites, such as glass fibre, epoxy, carbon fibre composites, materials with honeycomb structures, and then also some of the plastic. [10]

Factors we should consider, when selecting materials, include operating temperatures, corrosion exposure, loading conditions, moisture, but also noise levels, regulatory and economic considerations. For instance, wings for fixed wing drones endure various stresses such as torsion, bending, tension etc. Thus, key requirements for material demand tensile strength, stiffness, buckling strength and vibration resistance. [38]

2.3.1.1. Composites

Many different materials can be utilized for UAVs, but the current trend seems to be toward composites as it offers several benefits e.g., high strength to weight ratio, and strong structures that can be built without utilizing expensive equipment. [10] Both fibre metal laminates (FML) and fibre-reinforced polymers are advanced composites that boast superior specific strength and stiffness compared to traditional materials and most metals and for this reason they gained significant traction in several applications including aerospace. Carbon fibre-reinforced polymers (CFRP) rank among the most widely utilized materials in aerospace alongside aluminium alloys. They are found in applications such as elevators, rudders, and ailerons. Glass fibre-reinforced polymers (GFRP) are most suitable for semi-structural elements (e.g., fairings) and radomes. Lastly, aramid fibre polymers are the best for applications that require high impact resistance. FML, particularly GLARE (glass fibre reinforced aluminium) offers reduced density, high stiffness, strength, and fatigue resistance and found applications in critical areas, those include e.g. empennages and fuselage skins. [38]

Carbon fibre composites

Carbon fibre composite has an exceptional tensile strength and thermal conductivity, high rigidity, and low density and these properties are the reason why it is a top choice in industrial and aerospace applications. In comparison to e.g., fiberglass and Kevlar, carbon fibre composite offers the highest strength. It is a preferred replacement for titanium and aluminium alloys for components utilized in aerospace sector. Carbon fibre is best used with epoxy resins while utilizing vacuum equipment. This can significantly enhance the quality of laminates. Material is suitable for use in applications utilized in outside conditions as it has low thermal expansion – meaning it will not change shape or shrink with seasonal weather conditions. In terms of manufacturability, special tooling and processes are not necessary, making it easy to fabricate. The main disadvantages are that it has high cost, high EMI shielding properties and breaks suddenly. [9]

Fibreglass

Fibreglass is the most utilized fabric in composites nowadays due to its physical properties and low cost, making it great choice for both, hobbyists, and professionals. Composites made from fibreglass are lightweighted and strong. Two main types are used today – S-Glass and E-Glass. Due to its conductive nature, E-Glass was developed for electrical purposes and one of the applications is use as a secondary bonding between carbon fibre and metal parts. S-Glass offers greater stiffness and impact resistance, and it has approximately 20% better strength characteristics. This material is excellent for outer layers. [9]

Kevlar

Kevlar offers several advantages whether it is utilized as a light, tough fabric or in composite form. This material bridges the gap between carbon fibre and fibre glass. When integrated into composites, we can produce structures with superior abrasion and impact resistance. However, processing Kevlar is usually challenging as it is difficult to cut and prepare, and another disadvantage is that this material must be painted to prevent degradation from sunlight exposure and UV radiation. Another information to watch for is the fact, that fibres absorb water (~3.5%). Common applications are automotive body parts, motorsports protection, and high-performance aerospace structures. [9]

2.3.1.2. Polymer materials

There are several plastic materials utilized for UAVs. As the most suitable, we should consider PLA (Polylactide), ABS (Acrylonitrile Butadiene Styrene) and Nylon.

- **PLA** is a thermoplastic polyester that offers stiffness and maintains strength at a lower production cost while also having a biodegradable nature.[39]

- **ABS**, another common thermoplastic polymer used in 3D printing (3DP). It is composed of three different monomers: acrylonitrile, butadiene, and styrene that contribute to its unique characteristics. It stands out for its durability, impact resistance, cheap price, and provide structural integrity without adding excessive weight at a competitive price point. As we can see from the table 3, ABS has very low mass density, actually the lowest from these three selected plastic materials. [23, 39]
  Manufacturability is not really good as it is prone to shrinkage and warping during the printing process. This can lead to dimensional inaccuracies. But in terms of post-processing, this material is very pleasant to use as it can be painted, glued, and sanded. While ABS has good temperature resistance, it is one of the materials with hygroscopic properties that make it take up and retain moisture. Another disadvantage is that it has negative impact on environment if it is not properly recycled. [23]

- **Nylon**, as a family of synthetic polymers, on the other hand, promises flexibility, high tensile strength and a balance between weight efficiency and durability. [39]

Table 3: Some of the properties of selected plastic material. [39]

Properties	Nylon 6/6	ABS	PLA
Yield strength [MPA]	82.75	20	49.5
Mass density $\left[\frac{g}{cm^3}\right]$	1.13	1.06	1.3
Ultimate tensile strength [MPa]	82.75	29.6	50
Poisson's ratio [-]	0.35	0.38	0.39
Young's modulus [GPa]	2.93	2.24	3.5
Shear modulus [MPa]	1000	805	2399.99

PMMA

PMMA (Polymethyl methacrylate) is material with exceptional impact resistance, weatherability, lightweight characteristics, and durable nature, and it is a highly demanded product as it is utilized in applications such as interior components in aircrafts, aircraft windows, and canopies. The aviation market with PMMA is experiencing significant growth that is driven by growing emphasis on sustainability and fuel efficiency and this market is set for substantial growth in the coming years too. Another notable trend happening in aviation plastic market is due to the development of surface treatments and coatings especially designed to enhance the durability and performance of PMMA in aviation applications. Manufacturers are also trying to improve the cost-effectiveness and efficiency of PMMA production by coming up with innovations in processing technologies. [3]

PMP

PMP (Polymethylpentene), also known as Poly(4-metyl-1-pentene), is a versatile thermoplastic polymer that is a member of the polyolefin family. This material has outstanding chemical resistance to a wide array of chemicals, low density as it is one of the lightest thermoplastics available, heat resistance allowing it to be used at elevated temperatures, and last key property is an electrical insulation. These properties make the material beneficial for use in aggressive chemical environments, in the aerospace and automotive industries, and it is suitable for electronic and electrical components, where dielectric strength and transparency are favourable. The main challenges of using PMP are limited availability in some regions, and cost considerations as this material is relatively expensive compared to other thermoplastics. [40]

PETG

PETG (Polyethylene terephthalate glycol) is highly utilized thermoplastic in 3D printing technology due to its transparency, good printability, low density, exceptional impact performance, chemical alkali resistance, and furthermore, with specific print settings, we can obtain excellent layer adhesion and minimal shrinkage. [8] PETG has good manufacturability properties as it is easily printable and has excellent adhesion. The weather resistance in general is average as it is resistant to UV light and in general used outdoors, but this material is hygroscopic meaning it easily absorbs and retain moisture. [23]

However, there are studies that present idea of adding carbon fibres to make the material more resilient and resistant, making it extend field of applications to industry, automotive and aeronautical sector. Sara Valvez (2022) examined 3D printed PETG composites reinforced with Kevlar, and carbon fibres with material testing to reveal mechanical strength. When reinforced with fibres, attractiveness of PETG increases further. Static characterization revealed that the highest compressive modulus was in PETG with carbon fibres, whereas the lowest was in PETG with Kevlar fibres. [8]

Polyurethane

Polyurethane (PUR) is a versatile class of polymers often associated with paints, coatings, but it can also be used as flexible or rigid foams. This lightweight material can be customized because there of the existence of thermosetting and thermoplastic polyurethanes that allow it to be beneficial in automotive, construction, and electrical industries. Rigid polyurethane foams are the most energy-efficient and economical materials as in some cases, it is possible to create low-density foam with only 3% of the total volume being made up of solid PUR. [22]

2.3.1.3. Metals

Engineers in Advanced Structures India made study and analysis of materials, surface coatings, manufacturing methods, and other information about DJI Inspire 1 drone. They found out that plastic materials are the most utilized ones with 53.1% of all the materials present on components. Composites comes as the second one, and they are followed by metals such as Steel, Aluminium and Copper. Majority of metal materials is used for fasteners, and some metals are utilized for surface coatings e.g., zinc. [24]

In conclusion, metals are not widely used materials for drone components as they are heavier than plastic and composites. If it would be necessary to utilize metal in some structure, we can try to think about foam metal.

Foam metal is a cellular structure filled with voids from air which results in a reduction in weight. Metal foams can be utilized to produce sandwich materials, which provides higher fracture toughness and tensile strength. [38]

2.3.2. Previous studies

This chapter delves into the previous researches focused on specific materials and practices. Overview of historical and recent developments can help us in understanding the behaviours and properties of some selected materials and contextualize research for our project.

Earlier examples of research into carbon materials and their electromagnetic interference shielding effectiveness are included in paper of Chung, 2000. He made a review by examining various carbon materials - they encompass graphite and composite materials. [21] Another paper presents a testing methodology for radomes. [18] And the last research investigated Glass Fiber Reinforced Polymer composites to determine the dielectric loss tangent and the relative permittivity. [17]

2.3.2.1. Composite materials for shielding

In his paper, Chung 2000, discusses that a composite material having a conductive filler with a small unit size of the filler is more effective than one having a large unit size due to the skin effect. Therefore, a filler of unit size 1 micrometre or less is preferred. The following materials were analysed:

- Polymer-matrix composites with conductive fillers - they are commonly electrically insulating and attractive in their low density for shielding. Continuous fibre polymer-matrix structural composites are in aircraft and electronic applications utilized for EMI shielding.
- The use of a cement matrix is also an interesting choice as it is slightly conducting and offers higher shielding effectiveness than polymer-matrix composites. A shielding effectiveness of 40 dB at 1 GHz of this composite and the fact that it is less expensive than polymers is making this choice a useful one, but the best application is for rooms in buildings, not UAVs.
- Carbon is due to its conductivity a superior matrix compared to polymers, but it is a more expensive choice. EMI shielding is one of the main applications of short carbon fibres. Carbon filaments of submicron diameter, typically around 10 micrometres, are often intercalated or coated with metals like nickel to enhance conductivity. [21]

Table 4: Electromagnetic interference shielding of different materials with matrix composites and various fillers at 1-2 GHz frequency [21]

Filler	Volume [%]	EMI shielding effectiveness (dB)
Al flakes (15 x 15 x 0.5 μm)	20	26
Steel fibers (diameter 1.6 μm x 30 - 56 μm)	20	42
Carbon fibers (diameter 10 μm x 400 μm)	20	19
Ni particles (diameter 1 - 5 μm)	9.4	23
Ni fibers (diameter 20 μm x 1 mm)	19	5
Ni fibers (diameter 2 μm x 2 mm)	7	58
Carbon filaments (diameter 0.1 μm x > 100 μm)	7	32
Ni filaments (diameter 0.4 μm x > 100 μm)	7	87

Due to their high conductivity, metals are a more attractive solution compared to carbons, but carbons offer oxidation resistance and thermal stability. The most desired metal fibres are the one with a small diameter. Metal fibres are made by forming or casting and with this production method, they cannot be finer than 2 micrometres. Nickel filaments are more attractive than for instance copper, because of superior oxidation resistance and their shielding effectiveness is 87 dB at 1GHz. [21]

The table 4 represents the EMI shielding effectiveness for composites with the same sample thickness (2.8 mm) but with various fillers at 1-2 GHz. The results were obtained with the coaxial cable method utilizing the same tester. [21]

2.3.2.2. Radomes

Qamar (2016) outlines a precise methodology for the testing of radomes intended for millimetre Wave applications and considers reflections, bandwidth, losses, incident angles and depolarization factors across varying frequencies. In his paper, he presents 4 radomes, including two monolithic and two sandwich structures, that were designed and tested and operated at 82 and 94 GHz. [18]

The radome serves as a crucial component in communication and radar systems to shield them, mainly the antenna, from environmental elements such as pollution, rain, and wind (e.g., wind loading), and ensure stability in varying environmental conditions such as humidity, temperature, and pressure while maintaining electromagnetic transparency. This transparency entails minimizing insertion loss, reflection, and polarization signal distortion.

The presence of a radome reduces maintenance and operational costs while extending the lifespan of the system. [18]

The emergence of millimetre-Wave frequencies has expanded the available radio frequencies for satellite communication systems and radar as it offers great. Especially W-band offers impressive data rate throughput capacity and attracts various communication technologies. [18]

Numerous materials suitable for radome design may exhibit limited resistance to heat. For instance, some materials can be tough at moderate temperature but become brittle at low temperatures. Moreover, even materials capable of withstanding high temperatures may experience significant alterations in their electric properties (e.g., permittivity). This change in permittivity across temperature variations can be calculated using the following expression.

$$\frac{\delta \varepsilon_r}{\varepsilon_r} = 2\alpha_t \delta T \tag{1}$$

ε_r - the change in relative permittivity
δT - the change in temperature
α_t - the thermal coefficient expansion (TCE) in ppm/°C [18]

Currently, a variety of materials are employed in the design of radomes having permittivity ranging from 1 to 10 and tangent-loss from 0.0003 to 0.011 within the W-band range. [18] The list of materials examined in the paper of Qamar (2016) is presented in the following table.

Table 5: Radome materials and their characteristics [18]

	Material	ε (W-band)	Tanδ (W-band)	TCE (Boresight) (ppm/ °C)
Core	RohaCell 51HF	1.048	0.0135	33.4
	Nomex	1.10	0.0030	-
	Divinyll cell HP	1.07	0.0030	40.0
	Polyurethane FR3703	1.04	0.0017	35.0
Skin	RO5880	2.19	0.0013	237
	PTFE Gortex	2.00	0.0002	-
	Fiber Glass-E	6.30	0.0037	5.00
	Fiber Glass-S	6.00	0.0020	2.90
	Fiber Glass-D	4.60	0.0015	3.00
	Kevlar 49	3.70	0.0020	-5.00
	Quartz	3.60	0.0120	0.55
Prepreg/bond ply	3M Adhesive	2.35	0.0250	5.84
	E-glass Epoxy	4.20	0.0160	6.30
	D-glass Epoxy	3.45	0.0090	8.90
	Spectra epoxy	2.80	0.0040	6.40
	Quartz epoxy	3.20	0.0110	7.20
Paint/coating	Hirec100	4.47	0.0139	-
	Cytonix	3.00	0.0200	-
	Esscolam10	3.00	0.0090	-

2.3.2.3. Glass Fiber Reinforced Polymer composites

Shafaat Ali (2021) investigated GFRP (Glass Fiber Reinforced Polymer) composite samples ensuring a balanced ratio of resins and fibres to determine the relative permittivity and dielectric loss tangent in his analysis to identify a potential candidate for future meta surface antenna applications. [17]

Due to superior advantages over conventional engineering materials, composite materials, reinforced with fibre of natural or synthetic materials, have gained significant traction in various applications and are increasingly in demand for their properties such as being lightweight. Fiber reinforced polymer composites have high fracture toughness, resistance to corrosion and thermal effects, high strength-to-weight ratio, exhibit excellent electrical properties and durability, and additionally, in their raw form, they are more cost-effective than other commercially available materials. [17]

Glass fibre is one of the most commonly utilized synthetic fibres. These fibres are classified into different families such as D-glass, E-glass, and S-glass, and they are combined with polymer matrices and fillers to form Glass Fiber Reinforced Polymer composites. [17]

In his paper, Shafaat Ali (2021) mentioned that meta surface antennas primarily utilized COTS (commercial off-the-shelf) substrates that can be expensive while he proposes idea of integrating GFRP-based composites into antenna designs as they are cost-effective alternative with favourable mechanical and electrical properties. [17]

Table 6: GFRP composite samples and their material composition [17]

Sample ID	Sample Image	Material Composition
X		**Reinforcement:** Chopped E-glass fibermat, Density 450 g m^{-2}, sample thickness 2.32 mm. **Matrix:** Thermoset epoxy resin (Bisphenol-A) with hardener (Cycloaliphatic amine), Ratio of epoxy to hardener was kept 10:3.5 by weight. **Number of Layers:** 05 **Make (Matrix):** (Huntsman, Germany)
Y		**Reinforcement:** E-Glass fiber peel ply, Linear Density 200 g m^{-2}, Plain weave, sample thickness 2.62 mm. **Matrix:** Araldite GY 6010 epoxy resin with medium viscosity and high shelf life. **Number of Layers:** 15 **Make (Matrix):** (Huntsman, Germany)
Z		**Reinforcement:** Chopped E-glass fiber mat, Density 450 g m^{-2}, sample thickness 3.20 mm. **Matrix:** Araldite GY 6010 epoxy resin with medium viscosity and high shelf life. **Number of Layers:** 25 **Make (Matrix):** (Huntsman, Germany)

The electrical characterization of the GFRP composite samples involves determining their permeability μ_r, dielectric loss tangent $\tan\delta$, and permittivity ε_r. Then the conventional methods were utilized to calculate these properties based on the measured parameters S11 (Input Reflection Coefficient), S12 (Reverse Transmission Coefficient), S21 (Forward Transmission Coefficient), S22 (Output Reflection Coefficient). The choice of measuring method depends on various factors such as the sample length, the measured s-parameters, and desired dielectric properties. [17]

The table 7 represents results from the testing of different multi-layer GFRP samples with thickness around 2 to 3 mm. The fibre ply and the fibremat are arranged in three distinct orientations (0°, 45°, and 90°). The thicker the sample, the worse the permittivity. [17]

Table 7: Relative permittivity and dielectric loss tangent of GFRP composite samples [17]

Sample	Layers (No.)	Thickness (mm)	Frequency (GHz)	Relative Permittivity (ε_r)	Dielectric Loss Tangent ($\tan\delta$)
X	5	2.32	5.4 to 5.9	4.5 ~ 4.9	0.042 ~ 0.049
Y	15	2.62		4.83 ~ 5.32	0.008 ~ 0.012
Z	25	3.2		5.35 ~ 5.75	0.035 ~ 0.045

2.4. Antenna technology

Drones rely heavily on navigation/communication technology etc. for accurate position and navigation. The performance system and accuracy of positioning is significantly influenced by the placement of antenna, key considerations in selecting antennas and its design. In this section, we will explore different types of antennas commonly utilized in UAVs, and particularly those antennas optimized for GNSS reception. [29]

2.4.1. Types of antennas suitable for drones

In this section, we will talk a little bit about different types of antennas, their benefits and present a few photos of them.

2.4.1.1. Patch antenna

The patch antenna is a subtype of microstrip antenna, and it stands out as one of the most favoured GNSS types. Widely adopted today, it offers notable benefits for dynamic vehicles and their sleek design also proves advantageous in smaller budget-friendly consumer gadgets such as phones. [32, 34] At the following figure 7, a commercially available aviation patch antenna is presented. Rest of the figures show the following types of antennas available in stores.

2.4.1.2. Active antenna

Active antennas are used in the applications where there is a considerable cable length between the antenna and the receiver. This antenna incorporates low-noise amplifiers to amplify the received signal before it is delivered to the GNSS receiver. Beyond signal amplification, they may also decrease the overall noise figure of the receiver, resulting in better sensitivity. [26]

2.4.1.3. Dipole antenna

The half-wave dipole antenna is one of the most foundational electrically sensitive antennas. It is designed to operate near the resonance of the desired frequency. It is important to bear in mind that as the antenna size decreases to less than half-wavelength, together, its gain and efficiency are correspondingly diminished. [32]

2.4.1.4. Helical antenna

The characteristics of a helical antenna are an omnidirectional radiation pattern and high gain. This antenna is well-suited for GNSS reception in drones operating in dynamic environments. [34, 26]

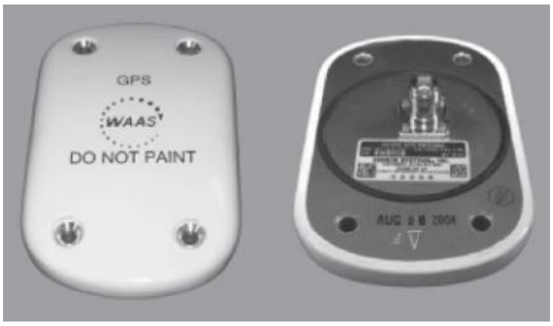

Figure 7: Patch antenna aviation form factors (with radome) [32]

Figure 9: Dual-Band Helical GNSS Antennas, Rugged Helicore GNSS antennas for GPS & GLONASS [26]

Figure 8: Half-Wave Dipole Omni-Antenna, Low-SWaP C-band antenna for UAVs and UGVs [26]

Figure 10: Single-Band Conformal Wave Antennas, Rugged L1 active antennas for GPS & GLONASS [4]

2.4.2. Role of antenna in navigation and positioning of drone

Currently, many GNSS receiver and antenna systems are utilized in several applications, including drones, and they vary in capabilities, size, complexity and cost - characteristics that are largely driven by the end-user application as a performance characteristic may be critical for one application and may not be desirable in another one. The leading requirement of the antenna is to convert the various signals from an electromagnetic wave to an electrical signal suitable for processing by the receiver. [32] To do this effectively, we have to consider several important performance characteristics during the designing process of the drone and during the selection of the antenna.

2.4.3. Antenna performance characteristics

- **Impact of antenna design and placement**

  They play a crucial role in the performance and accuracy of the GNSS system. Signal reception and position accuracy are affected by several factors such as radiation pattern, antenna gain, size, orientation. Properly selected placement of antenna is essential to minimize multipath effects, signal blockage, obstructions, and electromagnetic interference. [29, 34]

- **Frequency and bandwidth coverage**

  The antenna must have sufficient bandwidth to receive signals and must be sensitive to the signals' centre frequency. The following figure illustrates the various carrier frequencies in MHz and bandwidths in BW in the L-band in range from 1.1 GHz to 1.7 GHz for various GNSS bands. We can see that the various frequencies span a considerable amount of spectrum - this helps with ionosphere delay estimation that can be done effectively for dual/multifrequency users. The dual/multifrequency capabilities tend to find applications for more high-performance users. They have requirements for comprehensive ionosphere error mitigation. For most of the other applications, the single-frequency capabilities, such as general-purpose and low-cost, can be satisfactory. [32]

  Two main design approaches are employed for multifrequency antennas. The first approach entails a broadband design that aims to cover the entire frequency band. And while it provides specific coverage for each band, it optimizes performance across various bands. The second approach involves an antenna with multiple resonances. Typically, this approach is represented by dual-frequency, dual-layer patch antennas. They offer excellent performance over a limited bandwidth and in many cases, their disadvantage is that they may not cover the bands between the frequencies of interest. [32, 34]

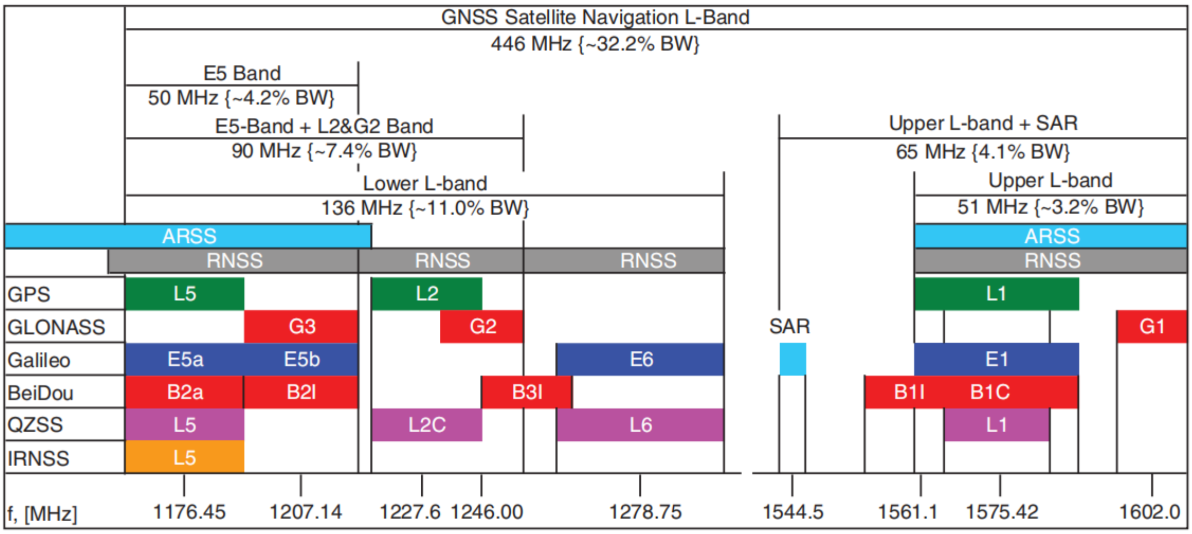

Figure 11: Various GNSS frequencies and bandwidths. [32]

- **Size and cost**

For some applications, the cost and size may be less constrained so that other performance requirements can be easily achieved. Good example for such an application is a fixed ground based GNSS reference station where the antenna is larger to produce high-quality code and carrier phase measurements. For other applications the size constraint can be based upon considering all of the functions to be performed by the application. [32, 34] In general, it is important to select a compact antenna to minimize weight. [29]

- **Radiation pattern characteristics**

Certain characteristics should be exhibited by the antennas' radiation pattern to accomplish the goal that the antenna has sufficient gain to effectively convert the electromagnetic wave into a signal voltage. [32] In some specific applications, a directional radiation pattern may offer better performance, and e.g., an omnidirectional antenna can provide uniform coverage. [29] For certain applications, the antenna size is significantly decreased, and they may have a more omnidirectional characteristic in all directions e.g., isotropic and there is a higher chance that they will be more affected by the other components around it. [32]

- **Antenna polarization and axial ratio**

While a diverse range of antenna types exist, most antennas are designed for right-hand circularly polarized signals to align with the polarization of incoming signals. The polarization of an electromagnetic wave is elliptical, while linear and circular polarization are special cases. The axial ratio refers to the sensitivity to the instantaneous electric field vector in two orthogonal polarization directions of the antenna, specifically, the maximum magnitude to the magnitude of the wave in the orthogonal direction. If we want to have an antenna with maximum sensitivity to the incoming signal, it should have an axial ratio of 1. In such a case, the electric field intensity vectors are the same in the orthogonal direction and in the direction of maximum sensitivity. [32] In conclusion, it is important to match antenna polarization with satellite signals as it ensures optimal signal reception. [29]

- **Directivity, efficiency, and gain of an antenna**

  The directivity is the ratio of the radiation intensity in a specific direction, normalized by the average intensity over the entire space. To maintain a more constant received signal power level, the directivity of the radiation characteristics is important. For instance, gain variations bigger than 18 dB across the coverage region of the satellite signals is too much. In the code tracking loops, it can cause significant cross-correlation issues. [14, 32] But generally in a challenging environment, higher gain enhances position accuracy and improves signal reception. [29]

- **Antenna impedance, standing wave ratio, return loss**

  Input impedance (Z) in omega, standing wave ratio and return loss are the performance parameters that can additionally help in some applications. [32]

- Lastly, if a person wants to do detailed research about antennas, he should also consider power consumption, power requirements, heat dissipation and compatibility with other components.

2.4.4. Communication and electronics components

Signal reception involves the antenna capturing signals transmitted by various GNSS constellations e.g., American GPS, Chinese BeiDou, European Galileo and Russian GLONASS. Signals contain timing information in transmitted code and phase which can be used for positioning. Additional corrections are provided by Satellite-based augmentation system (SBAS). The next step is signal processing. The information embedded in the signals includes extracting timing and positioning data to calculate the drone's position, orientation, and velocity based on the time difference between signals received from multiple satellites. This information is decoded by the receiver and after processing, algorithms are utilized to calculate the drone's precision position (latitude, longitude, and altitude) relative to the Earth's surface. The position information is integrated into the control system of the drone, that is including the autopilot system or flight controller. To maintain the desired trajectory and position, these systems adjust flight parameters, including pitch, roll, yaw, and throttle.

This closed-loop feedback system helps ensure response to user commands and adapts to changes in the environment. [29]

Storage devices are essential components utilized to store configuration settings, data, and software necessary for communication between satellite constellations, antenna, and receivers. A common reliable solution utilized as a storage device is onboard flash memory that is accessible by the onboard computer or the flight controller to maintain communication with the receiver and execute commands. In terms of drones, navigation software, critical data, and the firmware of the flight controller are stored in onboard flash memory. It helps to facilitate communication and additionally, it allows improved responsiveness during flight control and faster access to essential resources. [29]

A drone is usually exposed to mechanical stresses. These can include free fall, drops or simple vibrations. When designing drones and selecting storage devices, we should avoid the ones with mechanical parts or connectors or optical storage devices. The key parameters such as storage capacity, size, security features, host interface, operating voltage and cost should be checked before selecting a storage device. The ideal solution is a storage device soldered down on the board such as uSSD (Unstructured Supplementary Service Data) and eMMC (embedded multimedia card) devices. [29]

2.4.5. Frequency of GNSS receiver

There are two main types of GNSS receivers – single- and dual- (or multi-) frequency receivers. What are their differences? And which one is the most suitable for our drone?

2.4.5.1. Single-frequency receiver

Single frequency receivers are highly dependent on ionospheric models which are internal or provided as additional corrections by SBAS systems. Positioning during major ionospheric disturbances is almost useless for precise geolocation. [2, 7] These are the reasons why we are not willing to search for those receivers as they are not really useful for our application.

2.4.5.2. Dual-frequency and multi-frequency receiver

A dual-frequency receiver and multi-frequency receiver are receivers capable of processing signals across two or more frequency bands from each satellite system. The primary difference between single and dual (or multi) frequency receivers is the enhanced accuracy achievable by removing the first-order ionospheric errors. Benefit of Dual-frequency receivers is that they have sufficient GNSS signal reception even under degraded conditions. [2, 7, 25] The limits of GNSS technology are being pushed by multi-frequency receivers to achieve the most reliable, robust, and accurate positioning possible. [25] Multi frequency systems help to minimize errors. But errors can still be several meters even in advanced solutions, not only in the evaluated height, but also in the position on the map. [2, 7]

On top of robust performance in difficult environments, what are the benefits of using such receivers e.g., in drone GNSS systems and how do they improve positioning?

- With access to multiple signals from the same satellite, a receiver can eliminate significant ionospheric errors, while the accuracy will be reduced from several meters to just one meter.
- Better multipath rejection because multi-frequency GNSS receivers integrate sophisticated algorithms to be resilient against the multipath interference. Meanwhile the single frequency receivers are vulnerable to this interference where direct signals are distorted by reflections off objects such as buildings, and vehicles.
- An RTK fix provides the highest level of positioning accuracy. Achieving it in single frequency receivers can require several minutes. However, with a receiver capable of tracking multiple signals, the convergence time is reduced to several seconds. This capability is crucial in challenging environments where positioning might be occasionally lost and needs to be quickly reacquired. [25]

2.4.6. Accuracy of GNSS receiver

Throughout this thesis, the term 'accuracy' is used to refer to the closeness of the result of a calculated position by GNSS to the correct value of the real position of the drone, and it also defines the radius of the circle of unknown around a given point. Over measuring time, GNSS is able to plot multiple different positions for a true point. It has become commonplace to distinguish different types and levels of an occurred errors: ones caused by variables in the GNSS satellites, errors and propagation delays caused by ionospheric scintillations causing degradation of the system performance, and effects of the surrounding physical environment. [2, 6] The long-term impact of research on GNSS has made great progress in correcting for errors and offering an adequate explanation of them. However, one major drawback is that the real-time accuracy of a receiver is dependent on its ability to process corrections.

With respect to accuracy, it is also necessary here to clarify exactly what is meant by 'precision'. Precision may be defined as repeatability - how frequently a receiver in successive measurements of the same true point taken under the same conditions can plot a point inside the circle of accuracy. If the accuracy is with e.g., 87% precision, it means that 87% of the time, a point will be plotted within one meter of the given point. The calculation of this precision has not been consistent and has been extended to refer to industry-standard statistical analyses and we can use Circular Error Probable (CEP), 2-dimensional RMS (2DRMS), Radius 95% (R95) and Root Mean Square (RMS) to find out the value of precision. [6]

From the figure 12 we can see that notable differences have been found between the scatter plots plotted by a receiver with incompatible precisions.

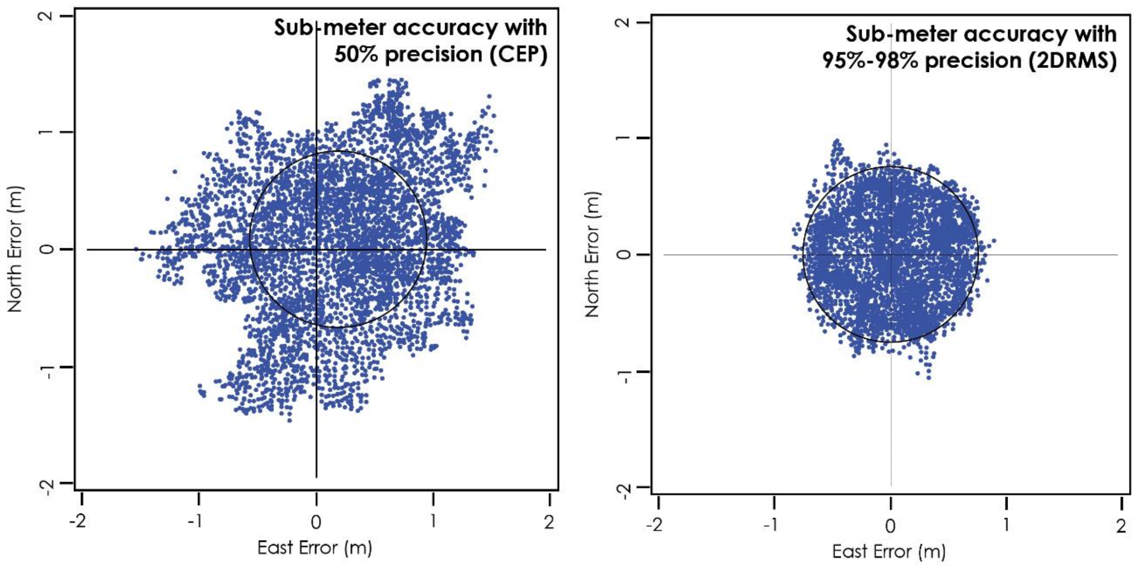

Figure 12: The points plotted by a receiver form a scatter plot with different precisions [6]

2.4.7. Selected antenna

In this section, we will do research about receiving antennas often utilized in drones for similar applications. Three following antennas - Holybro Pixhawk 4 Neo, H-RTK F9P Rover Lite, and Emlid Reach M2/M+ LoRa radio - turn out to be the most suitable for us and we will need to compare their characteristics, and price.

2.4.7.1. Holybro Pixhawk 4 Neo

This Holybro product is compatible with the Pixhawk 4. It features an IST8310 compass, UBLOX M8N module, and a tri-colored LED indicator. The additional safety switch enhances the connection process. This module is configured with a baud rate of 38400 and operates at frequency 5 Hz. To mount the Pixhawk 4, we should use the provided foam pads and place it as close as possible to drone’s centre of gravity. [35]

Figure 13: Holybro Pixhawk 4 Neo-M8N GPS [35]

Data:
Ublox Neo-M8N module
Industry leading –167 dBm navigation sensitivity
LNA MAX2659ELT+
Rechargeable Farah capacitance
Low noise 3.3V regulator
Fix indicator LEDs
26cm Pixhawk4 compatible 10-pin cable included

Cold start:	26 s
Size:	25 x 25 x 4 mm ceramic patch antenna
Weight:	32 g with a case
Price:	around 60 €
Carbon rod:	70 and 140 mm [35]

2.4.7.2. H-RTK F9P Rover Lite

This antenna is the most suitable for geodetic usage and the best choice among the three options. It is designed specifically for high-precision positioning, and it is a part of the Here+ Real-Time Kinematic (RTK) system. It utilizes RTK technology that offers centimetre-level positioning accuracy. Overall, the H-RTK F9P Rover Lite is known for its reliability and ability to provide accurate positioning data even in challenging environments. [36]

Data:
Data and update rate (max): RAW: 20 Hz; RTK: 8Hz
Port: 26 cm PixHawk 4 compatible GH1.25 10 - pin cable included

GNSS	Galileo E1, E5, GPS L1, L2, GLONASS L1, L2, BeiDou B1, B2
LNA gain:	20,5 dBi
Antenna peak gain:	L1: 4 dBi, L2: 1 dBi
Working voltage:	4,75 - 5,25 V
Cold start:	29 s
Diameter:	76 mm
Height:	20 mm

Weight: 106 g
Price: around 370 € [36]

All H-RTK models include a GH 10-pin cable/connector that will ensure compatibility with the other products from Pixhawk family and other various autopilots. [36]

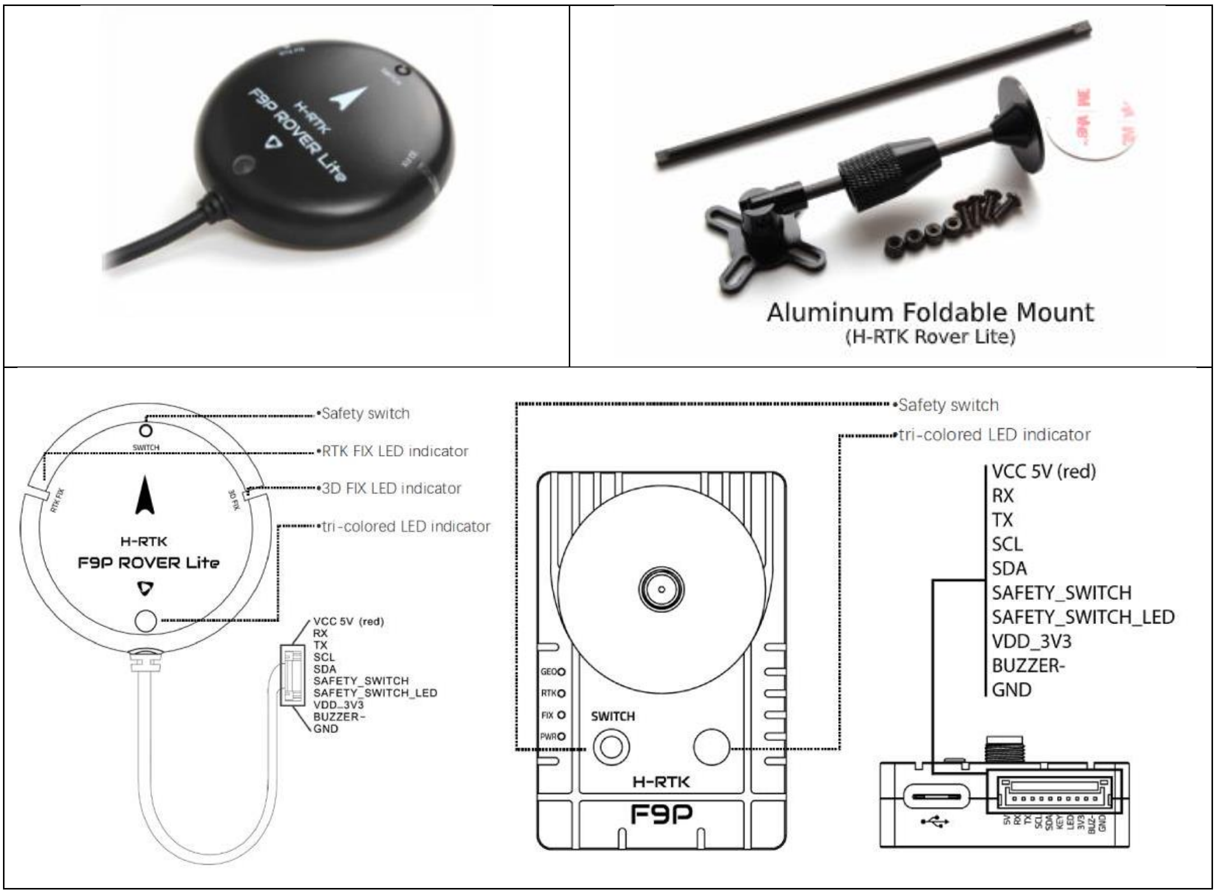

Figure 14: Left top picture: Rover lite product type of an antenna, right pic.: GPS accessory, the bottom pic.: pin map [36]

2.4.7.3. Emlid Reach M2/M+ LoRa radio

This antenna is designed for multi-band Real-Time Kinematic positioning. It offers centimetre-level accuracy and can be used for various applications, including mapping and surveying. However, it does not have the same level of precision and reliability as the H-RTK F9P Rover Lite antenna.

Data:
Frequency: 862 – 1020 MHz
Output power: 100 mW
Transmission range: up to 8 km
Antenna connector: RP-SMA

Weight:	17g, 32g with antenna
Dimensions:	50 x 29 x 19.6 mm
Price:	around 140 € [37]

Figure 15: EMLID REACH M2/M+ LORA RADIO antenna [37]

2.4.8. How to mount antenna to a drone

There are several decision factors to consider when thinking about mounting an antenna to a drone. These criteria include antenna placement and orientation on the UAV (or other application), cable routing, size of the drone, and ground plate or mounting platforms. In terms of mounting style, there are external and internal. This means that antenna can be mounted externally right on the cover of the drone, or internally under the cover where it embedded inside of the drone and hidden with rest of the electronics. The second style provides better protection against weather conditions and physical damage caused e.g., by impact with the building. Antennas are usually attached by small screws or if the drone frame allows it, it is convenient to ensure attachment with magnetic mounts.

We choose to mount the antenna under the cover of the drone which requires more careful selection of materials of the cover to ensure good signal reception. Antenna is attached on metallic platform in the centre of the drone. Since our selected antenna does not have any holes for screws, we can use double-sided tape to stick it on the surface of the platform of the drone.

2.5. Drones and casing system

2.5.1. Drone

What is a drone? An unmanned aerial vehicle (UAV) is a complex electromechanical system, also can be seen as an aircraft without a pilot/human onboard that is commonly known as a drone. An unmanned aircraft system includes UAV as one of the components, the other ones are a ground-based controller, and a system of communication and they are piloted by embedded computer programs or remote control. [29, 31]

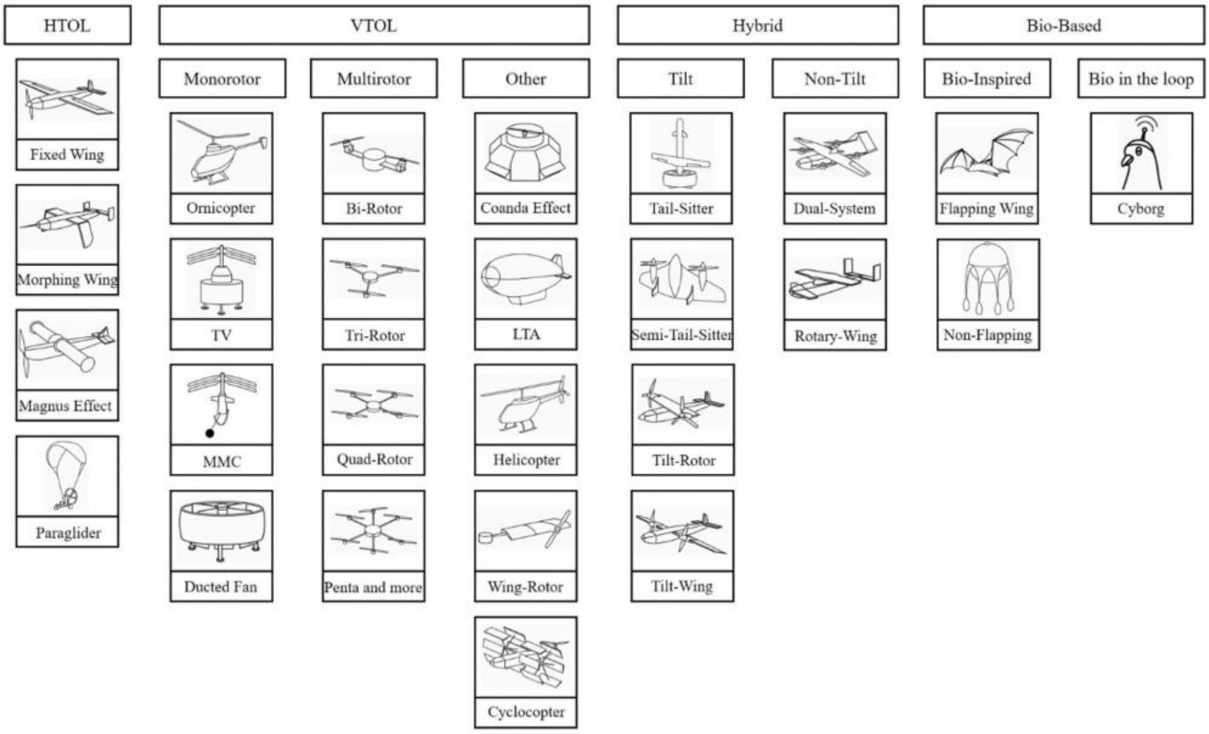

Figure 16: Different categories of UAVs [27]

2.5.1.1. Applications of drones

Throughout the history of UAV systems, drones have been usually driven by applications for military activities and deployed in hostile territory for armed attacks or remote surveillance to reduce pilot losses. And then, in recent years, followed by civilian and commercial applications once the testing and development has been completed and enthusiasm for using drones has skyrocketed. A number of titles have been employed for the air vehicles e.g., remotely piloted vehicle (RPV), unmanned aerial vehicle (UAV), radio-controlled plane (RC) (primarily used by hobbyists) and drones (= a pilotless airplane controlled by radio signals). Drones were a minority interest until around 2010 where they started to get the world's attention - the car company Parrot produced a multicopter AR.Drone controlled by an iPhone and Wi-Fi and constructed from nylon, polystyrene and carbon-fibre parts with option to mount a small camera. Nowadays, the term drone is used mainly for vehicles that fly in monotonous, persistently dull manner with limited flexibility for accomplishing sophisticated mission. UAVs can be controlled manually (means controlling the position by manually adjusting the altitude, speed, heading, attitude etc. through switches located in the ground control station) or via a preprogrammed navigation system (of various types e.g., GPS (global positioning system), inertial or radio that allow for preprogrammed missions). [10, 12, 31]

Drones utilized in applications for e.g., disaster management where the environment and the conditions are very chaotic and dangerous, it is important to acquire knowledge that helps with decision making. It is necessary to produce up-to-date information, as quickly and as reliably as possible in all weather conditions. [13]

Drones have caught the attention of both industry and academia due to their potential cost efficiency, low flying altitude and flexibility in comparison with conventional aircrafts. [31]

Numerous applications such as traffic control, photography, law enforcement, package delivery, search and rescue, air traffic management procedures, telecommunication, aerial inspections and precision agriculture, among others are suitable for use of UAVs. One of the initial tasks in drone configuration design is identifying the system's needs which serves as the basis for customer requirements (that create target values specified through negotiation with the customer) and establishing design criteria. Designers fall into 3 different categories: homebuilt, civil (industrial or enterprise group of applications that integrate drones and IoT (Internet of Things) technology and utilize drones with IoT sensor network in agricultural companies monitoring land and crops, and commercial targeted toward the professional community e.g., the movie industry, commercial agencies and for inspection of infrastructure) and military and prioritize design processes based on varied requirements, objectives and mission of the drone. Some of the primary factors that guide the drone design include aesthetics (shape, colour), material and its characteristics (e.g. weight and strength), producibility, performance of the drone, flying qualities, maintenance, and disposability. In 2017, the FAA (Federal Aviation Administration) launched a national program to explore the use of drones. This includes night-time operations, beyond-visual-line-of-sight flights (BVLoS) and flights above people. These new guidelines will accelerate the growth of the UAV industry and it is expected to create thousands of new jobs and offer fertile business opportunities. [29, 30, 31]

2.5.2. Cover

The cover of the drone is one of the fundamental parts of the assembly. In this following chapter we need to find out what are typically utilized covers for UAVs, what material is selected to manufacture such cover and if the material of the cover has led to the decline and attenuation of the signal transmitted into the receiver.

In the field of engineering, it’s common for the *cover* of the drone to have several different titles and names that will help the student, scientist or professional find this product. It is often referred to by acronym *shell* e.g., *top shell, body shell*. In some contexts, often commercial, it is labelled as a *casing*. And lastly, another frequently used name is a *canopy*. These various names refer to the same product, but each name might be used by different professionals and/or in different settings. Understanding these synonymous terms is important for effective research.

2.5.2.1. Research on different drones and their covers

Juniper (2018) uses various drones as examples of their specific applications, and he highlights their benefits and/or characteristics that stand out in comparison to other drones and UAVs.

Figure 17: From the top left to the bottom right: 1. DJI Phantom, 2. Yuneec Breeze, 3. DJI Inspire 2, 4. Powervision Powereye, 5. Sensefly Albris and 6. Hubsan X4 [12]

Figure 17, number 1 (DJI Phantom), 3 (DJI Inspire), and 4 (Powervision Powereye) are the drones that belong into a category of Prosumer drones that drive the consumer electronics industry. People using that equipment are always ready to have less mercy with UAVs as they want to utilize it in hostile conditions such as wind. Market offers a gust-resistant bigger drones with dual battery system, two times more expensive and durable frame and in some cases even retracting landing legs. [12] DJI Inspire drone series and their components are predominantly made of materials such as Carbon Fibre filament. [24]

Figure 17, number 2 - Yuneec Breeze belongs to a category of consumer-friendly drones that grow rapidly. Since it is expected that the drone will be used at vacations, the manufacturers are trying to solve the challenges of traveling by not choosing oversized batteries. Another obstacle are the sensitive components that need to be protected by covers, or if possible, eliminated. [12]

Figure 18: From the top left to the bottom right: 1. NLRobotic Y6 Pro, 2. Hubsan X4 H107D, 3. 3DR Solo, 4. Yuneec Q500 Typhoon, 5. Ghost Drone [12]

Figure 17, number 5 (Sensefly Albris) and figure 19, number 4 (DJI Matrice 600) are professional drones that need to be able to lift much heavier cameras with high-quality lenses and considering maneuverability, overall stability becomes a more important issue. The DJI Matrice 600 - a four-rotor drone has 3 different GPS receivers at the top so any potentially suspected data can be spotted much faster while comparing all three information. Those drones are useful e.g., for mapping and the GPS feature allows it to take photographs from specific locations. Other professional requirements are meeting safety requirements, so if some equipment of the drone fails another takes over, and resistance to dirt. [12]

Figure 17, number 6 - The Hubsan X4 is one of the very tiny drones that can land even on your hand. Those drones and their controllers are sold for less than a video game that is a very consumer-friendly option. [12]

Figure 18, number 1 - NLRobotic Y6 Pro has 6 motors and 6 rotors like a hexacopter, but it is achieved by putting two motors rotating in opposite directions on each arm. [12]

Figure 18, number 2 - Hubsan X4 H107D belongs into a category of indoor drones. It is fully charged in 30 minutes, and a flight time is 6 minutes. Recorded video can be sent in VGA resolution to the controller and saved to a Micro SD card. [12]

Figure 18, number 4 (Yuneec Q500 Typhoon) and figure 19, number 1 (Team BlackSheep (TBS) Discovery Pro'copter) and 3 (GoPro Karma drone) are examples of drones using motorized gimbals countering the drone's motion for stable videography and photography. [12]

Figure 19, number 2 - Parrot AR.Drone is a multicopter constructed as a consumer product that is ready to fly right away. Used materials for parts are carbon-fibre and nylon, and interchangeable hulls are made of polystyrene as it is a very light weight material. In front of the drone is a very small camera and the whole drone is controlled by an iPhone. At the time the drone was introduced in 2010 at the International Consumer Electronics Show (CES) in Las Vegas, the iPhone App store was only 18 months old, and it was a whole new world for the public. [12]

Figure 19, number 5 (Yuneec Tornado H920) is one example of drones with dual control to separate the control of the aircraft and the camera equipment to make it easier for production teams. Yuneec Tornado H920 is designed for dual- and single-operator flight and to carry the micro-four thirds camera the Panasonic Lumix GH4. [12]

Figure 19: From the top left to the bottom right: 1. Team BlackSheep (TBS) Discovery Pro'copter, 2. Parrot AR.Drone, 3. GoPro Karma drone, 4. DJI Matrice 600, and 5. Yuneec Tornado H920 [12]

2.5.2.2. Importance of having a cover on a drone

The incorporation of top and bottom covers is of importance as they serve as crucial protective elements. They shield the internal components of the drone from environmental conditions and hazards, operational tear and wear, and mechanical damage. The top cover guards against external elements e.g., rain, dust, and let's not forget UV radiation. The bottom cover provides additional protection against debris encountered during landing and low-altitude flights and against impact. Together, these covers ensure the reliability of sensitive electronics and sensors and also their longevity. Enhances structural integrity of the drone contributes to aerodynamic efficiency that leads to supported performance to optimum. Figure 20 serve as an example of what kind of electronic components, units, flight controller, and antenna with its accessories can be integrated in the inner part of each drone.

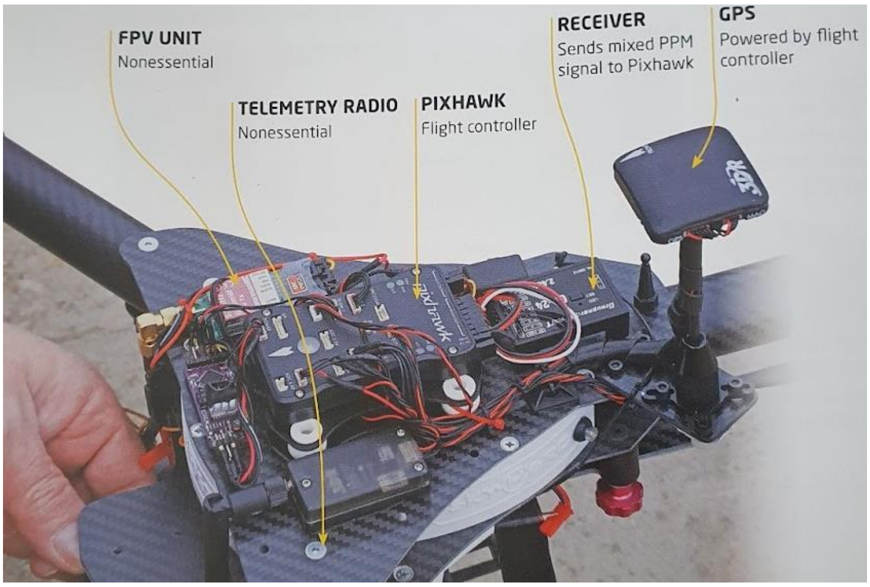

Figure 20: Y6 drone and its top of the Pixhawk flight controller with series of servo cables headed to Electronic Speed Controllers (ESCs) [12]

2.6. Material selection

Material selection is a fundamental aspect in this project and reviewing commonly used materials and analysing previous studies was guiding us to make informed decision. But first, let's see the table 8 with some of the selected materials and their information on dielectric constant. This can be one of the criteria in evaluation of materials.

Table 8: Materials suitable for drone's cover and their dielectric constant [19, 20]

Transparent plastic:	
Polycarbonate (PC)	2.90 - 3.20
Polycarbonate (PC) (20-40% Glass Fiber)	3.00 - 3.80
Polycarbonate (PC) high heat	2.80 - 3.80
Acrylic plastic (Polymethyl methacrylate (PMMA))	2.00 - 5.00
Other materials:	
PMMA (Acrylic) High Heat	3.20 - 4.00
PMMA (Acrylic) Impact Modified	2.90 - 3.70
(Borosilicate glass) D-Glass	3.80 - 4.80
ABS (Akrylonitrilbutadienstyren)	2.70 - 3.20
PMP (Polymethyl pentene)	2.10 - 3.60
PETG	3.00 - 4.00
Polyurethane (PUR) (Rigid foam)	1.03 - 1.21
Kevlar	3.50 - 4.50

Table 9: Material selection based on criteria [3, 8, 9, 23, 39, 40]

Material	Accessibility	Lightweight	Manufactu-rability	Weather resistance	Low cost	Final points	Test
PMP	0	1	0	1	0	2	No
Carbon Fibre Composite	1	1	1	1	0	4	Yes
Fibre glass	1	1	1	1	1	5	Yes
ABS	0	1	0	0	1	2	No
PETG	0	1	1	1	1	4	No
Kevlar	1	1	0	0	0	2	Yes
PMMA	1	1	1	1	1	5	Yes

When choosing materials for testing in analytical part of our project, we applied a rigorous set of criteria to make sure that the selected materials would be suitable for use in the drone. The criteria listed in the table 9 are accessibility in our laboratory, low density, ease of manufacturing process, weather resistance (including resistance to water absorption, UV resistance, suitability for outdoors environment), and cost-effectiveness. Zero means that the demanded characteristic is not fulfilled, and one means that it is accomplished. Here are the reasons behind the evaluation:

PMP

- It has limited availability in some regions that can cause problems in manufacturing process. [40]

Carbon Fibre composite

- The overall beauty of composites is that they can be manufacturing in several different ways and there is a big array of fibres, resins, twills, and weaves.
- It is resistant to different weather conditions as it is resistance to UV and moisture and suitable for outdoors. [9]

Fibre glass

- Manufacturing was evaluated as 1 because this material has high availability in different patterns.
- Cost is low as it has the best cost performance. [9]

ABS

- It has ease of post-processing, but manufacturing is worse as some processes can lead to some inaccuracies in dimensions.
- Evaluation of weather resistance was more difficult because this material has good temperature resistance, but it is hygroscopic. [23, 39] This property could be problematic for our future drone cover because we need to avoid materials that would retain water. Water can reflect incoming signals at some frequencies.

PETG

- As we can see from the table, PETG is very suitable material for use in our drone, but it was not available at the moment of selecting materials for testing. This is one of the materials recommended for the future research.

Kevlar

- The overall evaluation seems bad because it has high cost, and it is challenging to cut, prepare, and process. But we still decided to test the material in case, that these factors will not play high role for manufacturer or company of the product.

PMMA

- PMMA is a material with efficient production, utilized for windows and canopies in aerospace sector. Harrington Strategic (2024) mentioned in his article that manufacturers are focusing on innovations in processing methods. This is expected to lead to improved cost-effectiveness and higher efficiency in production of plastic in aviation sector. [3]

Metals

Additionally, we also decided to test two metal specimens – Aluminium alloy and Copper. As mentioned in the earlier section, these materials are utilized for few components in drones, and we would like to find out if they can somehow affect the signal propagation.

2.7. Conclusion of research

Our research project has reviewed existing studies, evaluated several materials that are already used for drone components, and some materials that have potential to be utilized for this application. We examined several properties and chose materials based on important criteria: density (has to be very low so the final product can be light), manufacturability (ease of processing, good printability, without tough challenges to prepare samples, and without limited availability), weather resistance (material should have good UV resistance, low thermal expansion, and it should not be hygroscopic to avoid retaining water and moisture), and cost (cheap price or cost-effective material is the best solution). We have selected the following materials for initial testing: Fibre glass, Kevlar, Carbon fibre composite, and PMMA. And additional specimens will be presenting Copper and Aluminium alloy.

The drone operates across multiple frequencies, including L1 and L2 (GPS and GLONASS), E1 and E5 and E6 (Galileo), for GNSS signals that ensure precise navigation, control, and accurate positioning, and 450 MHz – 3.8 GHz frequency range for 4G LTE and 450 MHz – 6 GHz frequency range for 5G that are critical for ensuring reliable communication.

For the antenna, we have selected Emlid Reach M2/M+ LoRa radio designed for multi-band RTK positioning. It ensures that the drone can achieve centimetre-level accuracy that is important for precise navigation and autonomous flight. This antenna does not have the level of precision and reliability as the H-RTK F9P Rover Lite antenna, but we still choose it as it is less expensive.

By integrating carefully selected materials and antenna technology, and after the forthcoming testing and evaluation phase, we aim to ensure that the final selection of materials provides the best possible choice for cover design and enhance the drone's performance and operational reliability while also balancing the overall weight, strength, and signal transmission efficiency.

Table 10: Summary of used frequency ranges

Communication or navigation system	Abbreviation of operating frequency range	Operating frequency carriers and ranges
GPS, GLONASS	L1	1 575.42 MHz
GPS, GLONASS	L2	1 227.6 MHz
Galileo	E1	1 559 – 1 592 MHz
Galileo	E5	1 164 – 1 215 MHz
Galileo	E6	1 260 – 1 300 MHz
4G LTE		450 MHz – 3.8 GHz
5G	Range 1	450 MHz – 6 GHz
	Range 2	24.25 – 52.6 GHz

3. Analytical part of the project

In this section of the research, we delve into the testing and analysis of selected materials to choose the best option from them and use it for the design of an optimal cover of our drone. The methodology part comprises of standardized calibration with calibration kit to optimally set the testing set up. Then we will move to a series of standardized tests of each material at different frequency range under same environmental conditions. Through data collection and analysis, we will seek to gain insights into the performance of each selected material specimen. Then we will highlight key findings, correlations and trends observed in obtained results and try to identify strengths and weaknesses in each material.

In the second part of the analytical part, we propose different design concepts for the cover of the drone and choose the best one. Finally, we engage in a discussion and draw conclusions where we reflect on the significant results, and their potential use for the future development or research.

3.1. Testing of material

Electromagnetic interference (EMI) shielding refers to the penetration - adsorption and/or reflection of electromagnetic radiation by different materials. For instance, at high frequencies (e.g. radio waves emanating from cellular phones) radiation tends to interfere with other electronics. The importance of EMI shielding is assigned to the reliability of electronics and the rapid growth of radiation sources. [21]

Designing a cover of the drone involves considering electromagnetic compatibility of different materials early in the product development process because testing shortly before the product launch could lead to budget overruns or delays due to some changes. Here are some key points to consider while defining an electromagnetic concept at the outset of the development project:

- Grounding: In general, define a grounding concept for the product (in other words a system grounding), subsystems (intrasystem grounding), and PCBAs (board-level grounding). [41] In terms of our project, it is not necessary to consider the last one.
- Shielding: Determine how and mainly if cables and sensitive circuits should be shielded. Try to find out if both within the system and externally. [41] Again, for our case, it is not important to go into such details, but in general, it is good to think about it.
- Filtering: Specify how cables and wires (internal and external) should be filtered, especially considering surge for cables leaving the product. RF-filtering should be considered for every cable. [41]

3.1.1. Methodology

Prior to conducting the tests of materials, we did preliminary research to gather relevant information and insights. This included interviews with a few companies specializing in manufacturing drones and trading to gain industry perspective. Additionally, we reviewed some of existing studies and literature on similar topics to understand previous findings. This analysis provided valuable context and helped us in terms of decision making and to conduct our own tests.

The methodology employed in this project involved an investigation of the electromagnetic properties of eight different material samples across five distinct frequency ranges, specifically 2.6 - 3,95 GHz, 3.95 - 5.85 GHz, 5.85 - 8.2 GHz, 8.2 - 12.4 GHz, 12.4 - 18 GHz. Selected materials from research section were Fibre glass, Kevlar, PMMA, and Carbon fibre composite. The primary objective was to assess whether these materials exhibit varying behaviours in terms of transmitting and/or reflecting electromagnetic signals. Additionally, we also conduct tests of Aluminium and Copper. The reasons are following: These materials are utilized for fasteners, additional plates where electronic components and/or antenna is placed and so on. We would like to know if these materials can somehow affect the signal transmission when utilized in the drone.

The tests are conducted utilizing specialized equipment capable of generating electromagnetic signals across a selected range of frequencies and each material specimen is subjected to the same laboratory environment and conditions to ensure consistency and reliability of the final results and to minimize external factors that could influence the outcomes.

Figure 21: Different sizes of waveguides

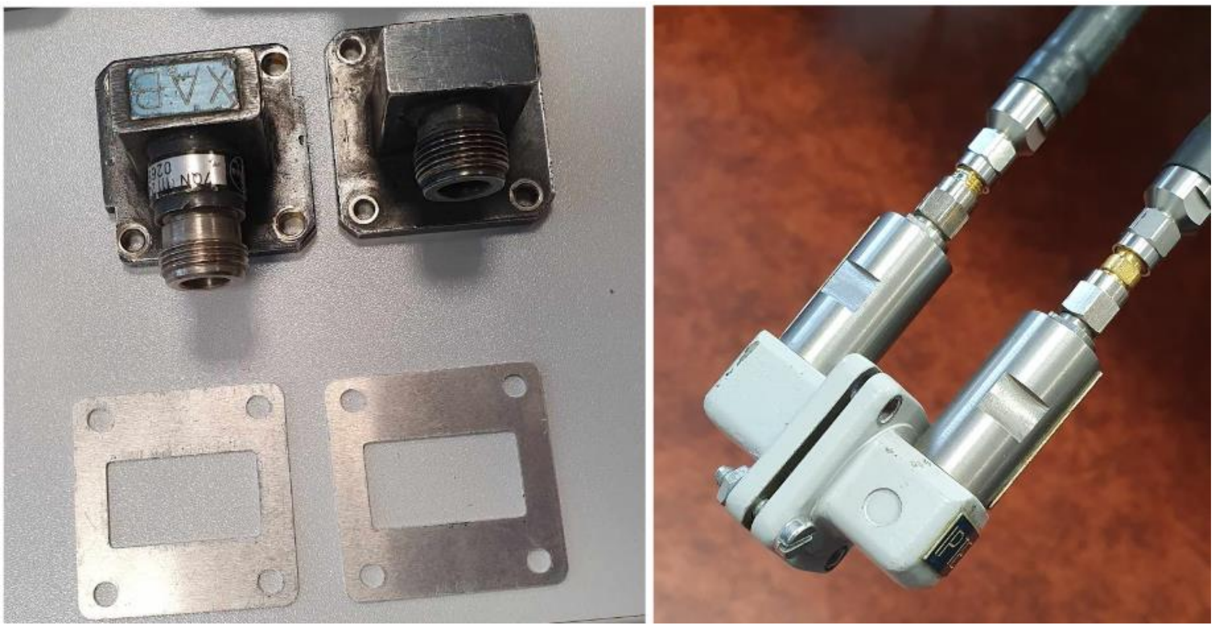

Figure 22: Additional aluminum rectangles for waveguides, and connected waveguides with rectangles and specimen in between during the test

Calibration before testing is crucial to mitigate errors, both repeatable and/or systematic. Calibration is utilized to subtract the effects of waveguides - they possess unique characteristics such as amplitude, phase shift, and losses. Values from the waveguide could introduce systematic errors into the measurement if we fail to subtract their effect. The utilized calibration method was TOSM (Through-Open-Short-Match). A calibration kit contains all the necessary elements for a comprehensive calibration. It is a set of physical calibration standards that is intended for a particular family of connectors. The ideal outcomes after calibration are the straight line at 0 dB for parameter S21, and -30 dB for parameter S11.

Table 11: Calibration kit and ideal standards for each type

Type of calibration	**Properties**	**Ideal standard**
Through	Connecting two ports together	-
Open	Open circuit – empty	∞Ω
Short	Short circuit with 1 port	0 Ω
Match	Adequate broadband connects with 1 port	Z_0

The open calibration was performed by connecting one port to a waveguide and calibrating it. A short calibration involved the attachment of a conductive plate to the connected waveguide and was conducted separately for both ports. The match calibration included a cable connected from one port to the first half of the waveguide, and a load Z_0 = 50 Ω was attached to the other half before assembling two parts together. The final step was the Through calibration is the final step where one part of the waveguide is connected to one port, and the other part to the second port. These two halves are assembled together and calibrated. Once the whole calibration process was completed and successful, the testing set up commenced.

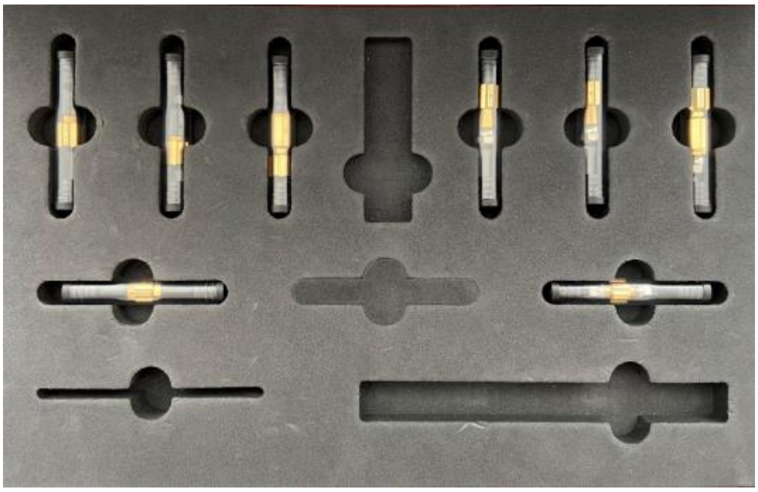

Figure 23: Calibration kit

3.1.2. Experiments

In this section, we will focus on the experimental methodology and describe procedures employed to test the chosen materials. The primary aim of the experiments is to evaluate if the materials are capable of transmitting and/or reflecting signals. The selected representatives of materials are Fibre glass, Kevlar, PMMA, Carbon fibre composite, chosen for their promising properties and potential compatibility in drone, and two metals, aluminium and copper that are used for some components in the drone. To conduct experiments, we prepared samples of each selected material to specific dimensions that fit the requirement size of testing apparatus. As an apparatus we are using waveguides that are specialized structures utilized to measure electromagnetic waves at different frequencies. Let's see how experimental set up looks like and how does it work.

3.1.2.1. Specimen selection

- For each selected material – Kevlar, Fibre glass, PMMA, Carbon fibre composite, Aluminium, and Copper, we had to select the material specimen with exact properties. We chose the following:
    - Fibre glass: Interglass 92 110 made by company Vertex, thickness: 2.8 mm
    - Kevlar thickness: 0.5 mm

- Carbon fibre composite thickness: 1 mm
- PMMA sample with transparent colour thickness: 3 mm
- PMMA sample with green colour thickness: 2 mm
- Aluminium alloy Dural thickness: 2 mm
- Aluminium alloy Dural thickness: 0.4 mm
- Copper thickness: 2.5 mm

3.1.2.2. Specimen preparation

The material samples had to be prepared before testing by trimming them to match the dimensions of the individual waveguides. At first, we started testing with bigger waveguides that needed specimens with bigger dimensions and subsequently, we cut them with scissors, saw etc. as waveguides tailored for higher frequencies are smaller.

Figure 25 presents the aspect ratio of waveguides and in table 12, we can see how big sizes A and B for each waveguide are that is utilized for different frequency range.

The dimensions of the samples were tailored to fit within each waveguide to ensure there is no loss in transmission or/and reflection of signals or that the measurements will not be influenced by the external environment.

Figure 24 shows 6 different material specimens. If we look from top left to the bottom right, we can see: Interglass, PMMA with transparent colour, Kevlar, Carbon fibre composite, Copper, and Aluminium.

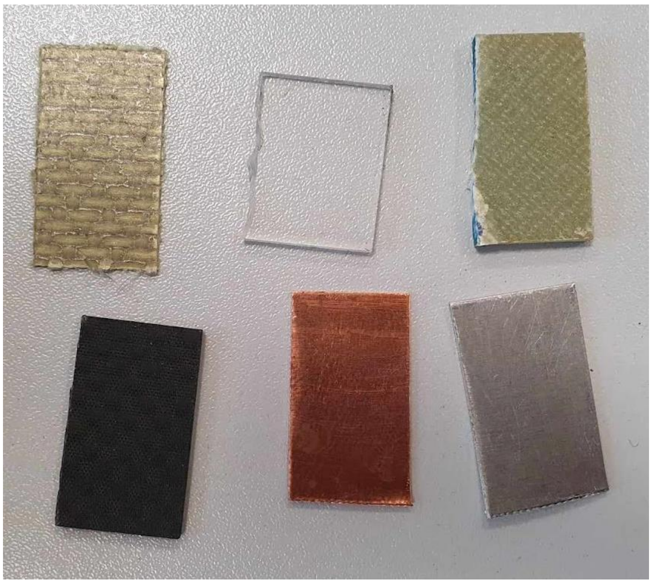

Figure 24: Specimens were progressively sliced into smaller segments to ensure a precise fit and to match the dimensions of the waveguides

3.1.2.3. Waveguide selection

To test a range of frequencies relevant to the operational band of the drone, we use different waveguides. The waveguides selected for this study include all five apparatus in the kit.

Table 12 shows information about each waveguide, what are their dimensions and what frequency range they operate on.

Table 12: Types of utilized waveguides

The name of the waveguide	Frequency [GHz]	Size A [mm]	Size B [mm]
R32	2.6 - 3.95	72.136	34.036
R48	3.95 - 5.85	47.5488	22.1488
R70	5.85 - 8.2	34.8488	15.7988
R100	8.2 - 12.4	22.86	10.16
R140	12.4 – 18	15.7988	7.8994

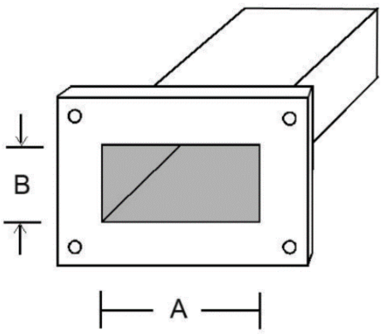

Figure 25: Sizes of the waveguide

3.1.2.4. Understanding the testing equipment

A Vector Network Analyzer (VNA) has a front panel that consists of a colour display providing all control elements and next to it are softkey area and the hardkey are on the right side, as seen on figure 28.

Area with test ports is below and it serve as outputs for the RF stimulus signals and as inputs for the measured signals. With one test port, it is possible to generate signal and measure the response in reflection. With more ports, we can see S-parameters.

To set the sweep range for all channels, we can do it with the following method: Right-click the start value in the channel list and from the context menu select the buttons: *Start, Stop, Center* and *Span*.

Table 13: Example of the sweep range

Ch1	Start 5.85 GHz	Pwr -10 dBm	Stop 8.2 GHz

The equipment provides a variety of functions. Lets' look at the one that helps to perform a particular measurement that is followed by customizing and optimizing the results. The following figure presents how the instrument is creating user-friendly environment where the data can be stored.

Global resources correspond with connection types and have their hardware-related settings.

A set up is a set of diagrams with all information that can be stored to a file.

Trace is a set of data points, and each trace is assigned to a channel. This channel contains hardware-related settings, and it helps to specify how the network analyser collects data. The displayed trace is composed of trace points that can be derived from the set of measurement points. Traces are the selection of the measured quantity. These can be wave quantities, impedances, ratios, and in our case, they are S-parameters. The default names for traces are Trc<n>, where n is number 1, 2 or 3. They are converted into the appropriate format in which we can read and search particular values.

The diagram area presents traces that are assigned to channels.

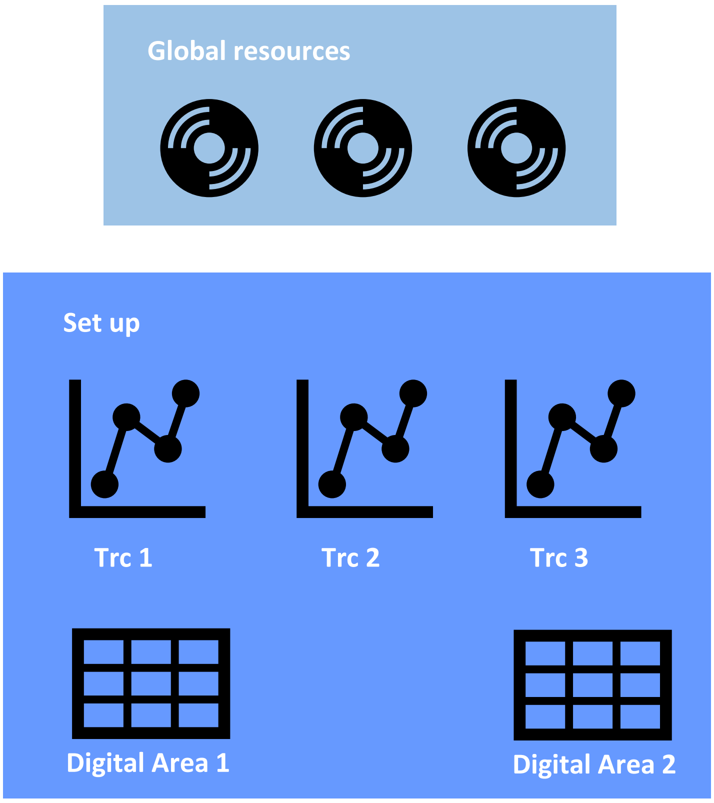

Figure 26: Basic concept of functions to perform measurement

If we look into the chapter Results and analysis at the first figure with diagram, we can see that this is Cartesian diagram, where the horizontal axis (x-axis) presents the stimulus variable linearly scaled into sweep type e.g., frequency, power, time, or they can be presented logarithmically e.g., log frequency. In our case, we can see the linear frequency range. The measured data appears on the vertical axis (y-axis) with the linear scale. Another type of diagrams used for evaluation of results can be polar diagrams and smith charts, but we will not utilize them.

S-parameters are the basic measured quantities describing how the specimen modifies signal.

- S11 (the input reflection coefficient) represents the amount of signal that is reflected back from the material. So, this parameter is utilized to determine the reflection of the material. It is measured at Port 1 and defined as the ratio of the wave quantities $\frac{b_1}{a_1}$.
- S21 (the forward transmission coefficient) indicates the amount of signal that passes through the specimen. It is the ratio $\frac{b_2}{a_1}$.
- S12 (the reverse transmission coefficient) defined as the ration $\frac{b_1}{a_2}$.
- S22 (the output reflection coefficient) defined as the ration $\frac{b_2}{a_2}$ of quantities measured at Port 2.

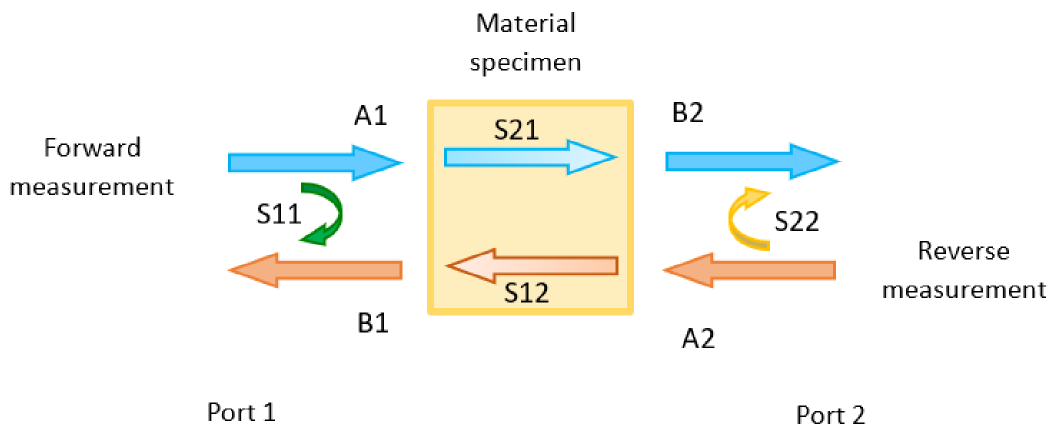

Figure 27: The signal flow for 2-port measurement

3.1.2.5. Testing procedure

Each sample was inserted into the appropriate waveguide. The biggest waveguide utilizes the lowest frequencies of the chosen spectrum. It is 2.6 - 3.95 GHz. Specimen had to be put into an aluminium rectangle of waveguide to minimize potential inaccuracies resulting from electromagnetic leakages along the waveguide flanks. Once the specimen was inserted, it was enclosed by the second half of the waveguide and securely fastened together by utilizing small screws.

Signal measurements were conducted using VNA to measure the S-parameters (scattering parameters) of each material specimen. Specific parameters are S11 (reflection coefficient) and S21 (transmission coefficient). They provide detailed information in saved waveforms where we can analyse how much of the signal was transmitted through the material during the test and how much of the signal was reflected back.

The VNA equipment performed a frequency sweep across the selected operational range of each waveguide and captured a profile of the electromagnetic properties of every material specimen. The whole testing equipment is presented at figure 28.

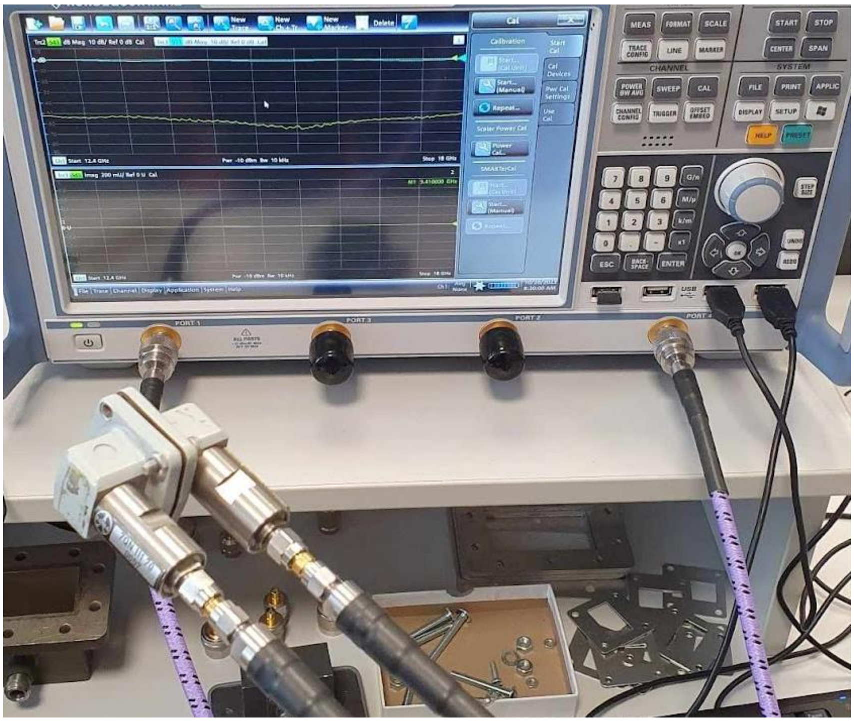

Figure 28: Testing of one material sample with specific waveguides on selected frequency range

3.1.2.6. Saving the data

Workspace allowed us to conduct the measurement process, their immediate assessment, and facilitate the evaluation of material properties by saving waveforms in MatLab format (.dat), Excel format (XLS), and graphic format (.svg) onto a USB (Universal Serial Bus) disk in the same location, ensuring all necessary resources were readily available.

The process was achieved by clicking the TRACE CONFID button, selecting EXPORT → IMPORT/EXPORT DATA → EXPORT DATA.

Other formats such as (.csv) are available, but the other ones were selected as they allow seamless data processing e.g., in the MatLab environment.

The exported data include utilized frequency, and S-parameters S11 (Input Reflection Coefficient) and S21 (Transmission Coefficient).

freq[Hz]	db:Trc1_S41	ang:Trc1_S41	db:Trc2_S41	ang:Trc2_S41	db:Trc3_S11	ang:Trc3_S11
2.60E+09	-1.27E+00	4.78E+01	-1.27E+00	4.78E+01	-2.20E+01	-1.46E+02
2.61E+09	-1.33E+00	4.62E+01	-1.33E+00	4.62E+01	-2.22E+01	-1.61E+02
2.61E+09	-1.32E+00	4.47E+01	-1.32E+00	4.47E+01	-2.25E+01	-1.75E+02
2.62E+09	-1.26E+00	4.32E+01	-1.26E+00	4.32E+01	-2.30E+01	1.71E+02
2.63E+09	-1.16E+00	4.14E+01	-1.16E+00	4.14E+01	-2.36E+01	1.58E+02
2.63E+09	-1.05E+00	3.92E+01	-1.05E+00	3.92E+01	-2.45E+01	1.42E+02
2.64E+09	-9.42E-01	3.69E+01	-9.42E-01	3.69E+01	-2.58E+01	1.24E+02
2.65E+09	-8.54E-01	3.44E+01	-8.54E-01	3.44E+01	-2.78E+01	1.01E+02
2.65E+09	-7.95E-01	3.18E+01	-7.95E-01	3.18E+01	-3.05E+01	6.96E+01
2.66E+09	-7.49E-01	2.92E+01	-7.49E-01	2.92E+01	-3.24E+01	1.66E+01
2.67E+09	-7.28E-01	2.66E+01	-7.28E-01	2.66E+01	-3.06E+01	-3.70E+01
2.67E+09	-7.09E-01	2.41E+01	-7.09E-01	2.41E+01	-2.68E+01	-7.11E+01
2.68E+09	-7.11E-01	2.16E+01	-7.11E-01	2.16E+01	-2.39E+01	-9.52E+01
2.69E+09	-7.05E-01	1.92E+01	-7.05E-01	1.92E+01	-2.18E+01	-1.14E+02
2.69E+09	-7.10E-01	1.70E+01	-7.10E-01	1.70E+01	-2.02E+01	-1.30E+02
2.70E+09	-6.97E-01	1.47E+01	-6.97E-01	1.47E+01	-1.90E+01	-1.46E+02

Figure 29: Example of exported data from VNA edited in Microsoft Office Excel

3.1.3. Results and analysis

In this chapter, we present the results of tests and detailed analysis. The material specimens were tested to determine suitability for use in the cover of the drone. Let's see how the individual samples performed in the tests.

Table 14: Selected materials and frequency ranges that were used for testing

Material/ Frequency in [GHz]	**2.6 – 3.95**	**3.95 – 5.85**	**5.85 – 8.2**	**8.2 – 12.4**	**12.4 – 18**
Aluminium thin	1	1	1	1	1
Aluminium thick	0	1	0	0	0
Carbon fibre composite	0	1	1	1	1
Copper	1	1	1	1	1
Interglass	0	1	1	1	1
Kevlar	1	1	1	1	1
PMMA thin	0	0	1	1	1
PMMA thick	1	1	1	1	1

3.1.3.1. Graphs evaluating reflection and transmission coefficients

In this section, we delved into the sharing of the most useful graphs that we obtained from the experiments using Vector Network Analyzer and waveguides. Our objective was to evaluate the performance of different material specimens at selected frequency ranges and also compare some of the results. The primary parameters of interest are S-parameters that provide insight into the transmission and reflection characteristics.

The results of measurements are shown in the form of graphs, with the x-axis representing frequency in GHz, and the y-axis representing values of S-parameters in decibels (dB), because dB are a logarithmic way of expressing ratios. Values on y-axis are negative to express the level of signal reduction.

The following graph represents the measurements that were conducted over a one range of frequency 3.95 – 5.85 GHz to capture the behaviour of each material specimen. The selected materials for representation were thin Aluminium alloy specimen with thickness of 0.4 mm, Carbon fibre composite, Interglass, Kevlar, and thicker PMMA specimen with thickness of 3 mm.

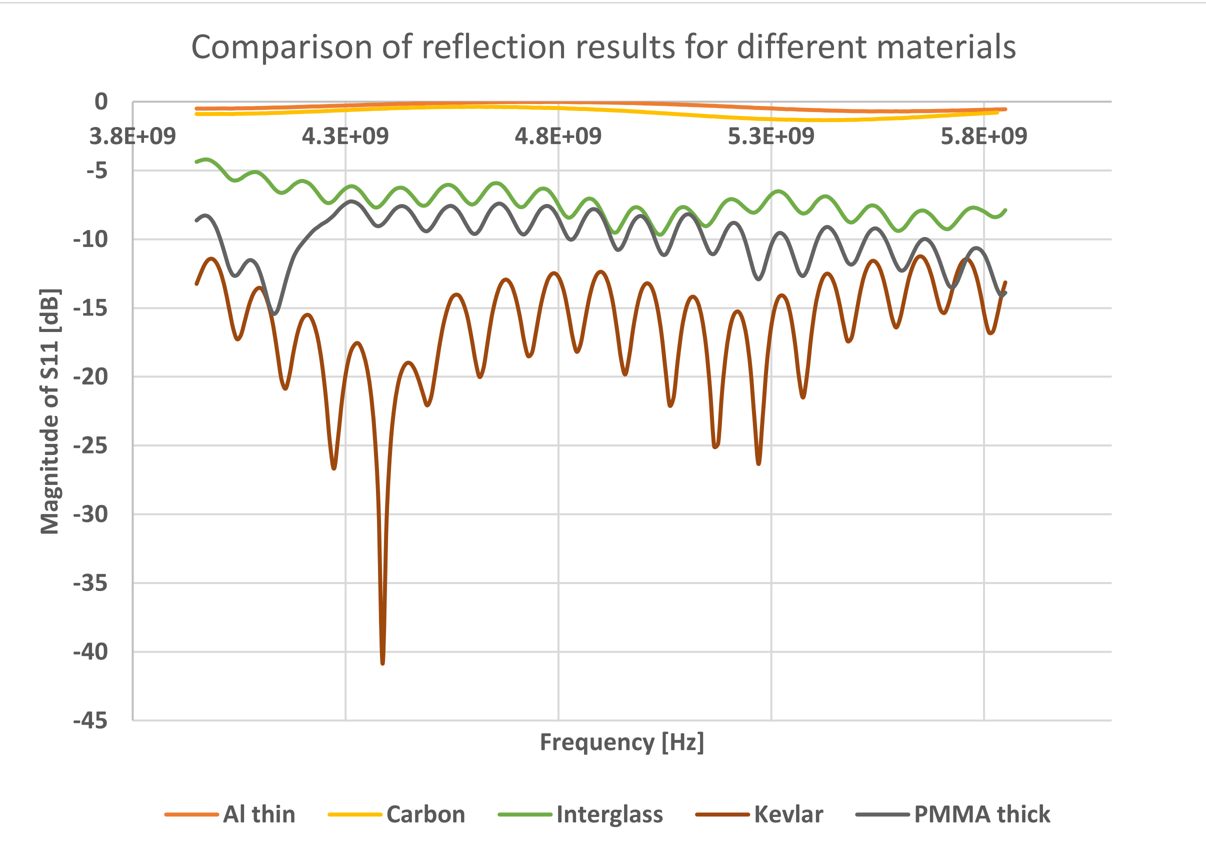

Figure 30: Comparison of reflection results for different materials

When comparing aluminium alloy (orange) and carbon fibre composite (yellow) to the rest of the materials, several observations were made. The high reflection values (around -1 dB) of those two materials indicate that a large portion of the electromagnetic wave is reflected, and very small portion will be either transmitted or absorbed. At figure 31, we can see that Aluminium alloy specimen is excellent reflector making it suitable for shielding applications. Other three material specimens (Kevlar, Interglass as a representative of glass fibre, and PMMA with thickness of 3 mm) allow transmission of signals with minimal reflection. Kevlar is especially expected to be effective in transmitting electromagnetic waves with minimal attenuation, The peak of minimum reflection is around frequency 4.3 GHz with magnitude exceeding -40 dB while rest of the reflection coefficient holds on to value around -17 dB. PMMA and Interglass show similar reflection coefficients around -9 dB, while PMMA is having its peak around the frequency 4 GHz with magnitude of reflection coefficient being around -16 dB.

The following figure 31 presents transmission of electromagnetic waves. Aluminium alloy specimen had very low transmission coefficient with magnitude oscillating between -80 dB to -105 dB, meaning that most of the electromagnetic wave is either reflected or absorbed.

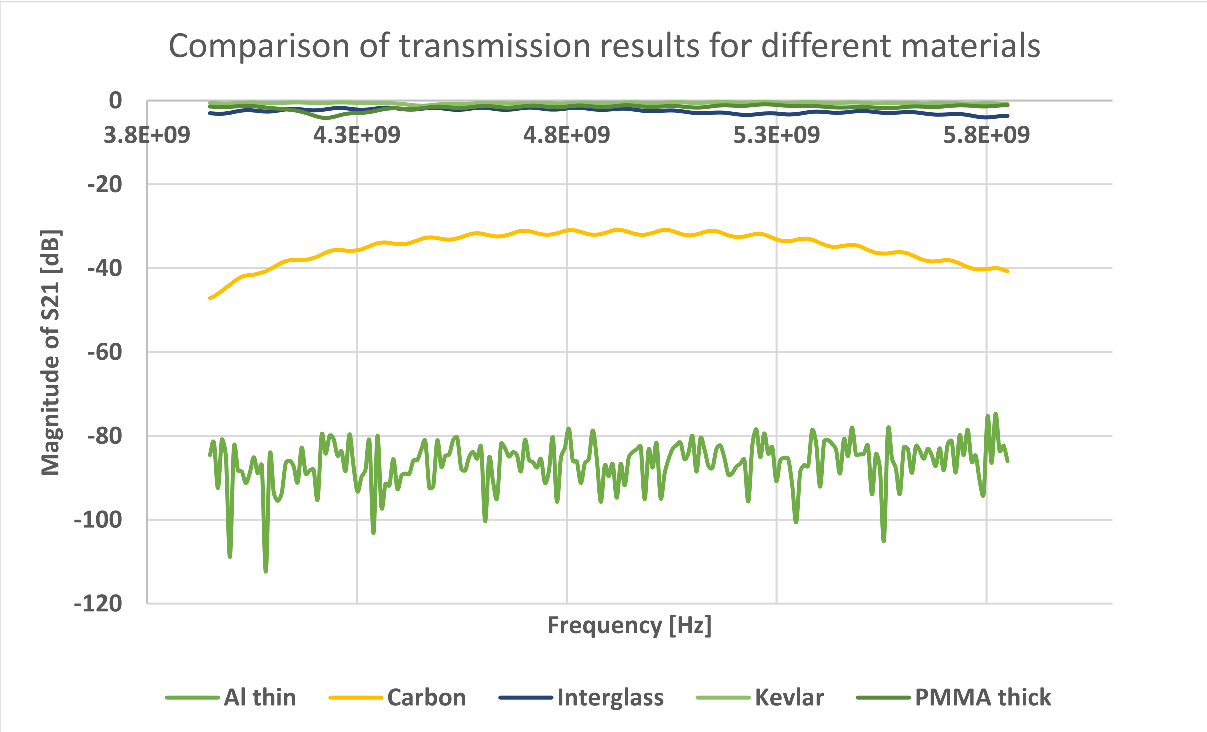

Figure 31: Comparison of transmission results for different materials

Results for carbon fibre composite show that it is not good choice for transmission of electromagnetic waves. Magnitude of S21 is around -35 dB that also indicates big portion of waves will be reflected or absorbed. Kevlar shows that it is especially effective in transmitting electromagnetic waves with minimal attenuation with magnitude around -1 dB. This means that most of the wave is being transmitted without being highly affected by absorption or reflection. PMMA shows transmission coefficient similar to Kevlar, here with magnitude around -2 dB, followed by results for Interglass with values around -3 dB. Results for these three material specimens indicate very good transmission with Kevlar having the best values.

For instance, now we take a look at detailed results of reflection coefficient S11 for Interglass specimen with thickness 2.8 mm at figure 32. We created graph where we represent results from measurements using all sizes of waveguides over all frequency ranges. This allows us to see and compare results at frequencies from 3.95 to 18 GHz. There is a certain smooth continuity of the course of the result, mainly between frequency ranges of 8.2 – 12.4 GHz and 12.4 – 18 GHz. Theoretically, experimental results should connect to each other in this way but at lower frequencies this connection is not so clear. This can be caused by many reasons. For instance, the selected material has certain properties, such as permeability, permittivity, and electrical conductivity - they can affect the given course of S11 magnitudes depending on the frequency. Another reason for unclear connections between individual results of experiments can be the fact that waveguides are easily affected by external influences that can introduce small errors into measurements. But this is the factor we tried to eliminate as much as possible, so the first reason more likely happen.

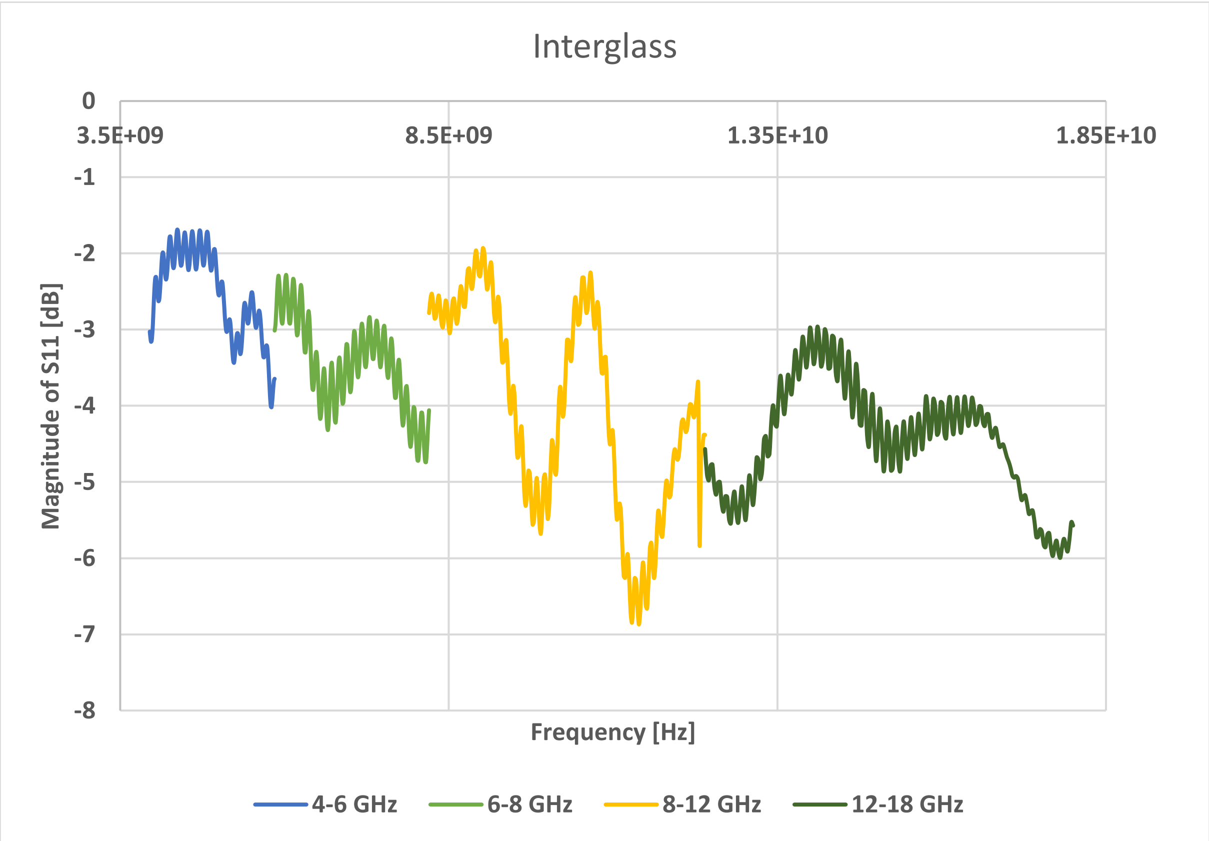

Figure 32: Results for Interglass over all frequency ranges

The following figure 33 show detailed results of transmission coefficient for Kevlar specimen with thickness 0.5 mm measured across the frequency range 2.6 – 3.95 GHz. At the beginning of the frequency range, the transmission is very low and has its minimum around frequency 2.6 GHz with magnitude for S21 of -1.3 dB. Rest of the results has smooth course with the maximum peak around -0.25 dB meaning that most of the signal can pass through the material.

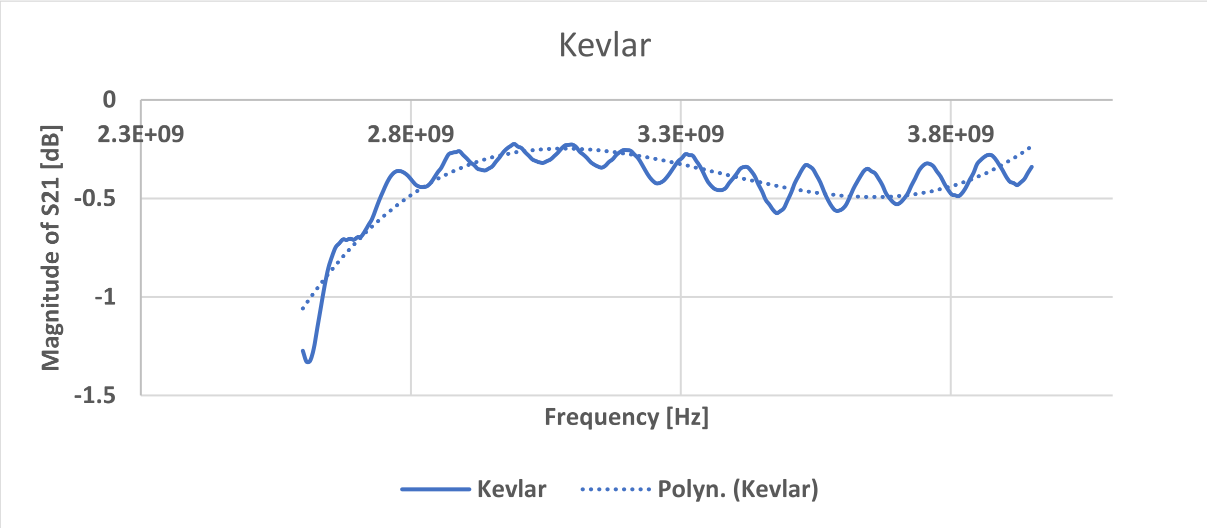

Figure 33: Results of S21 for Kevlar

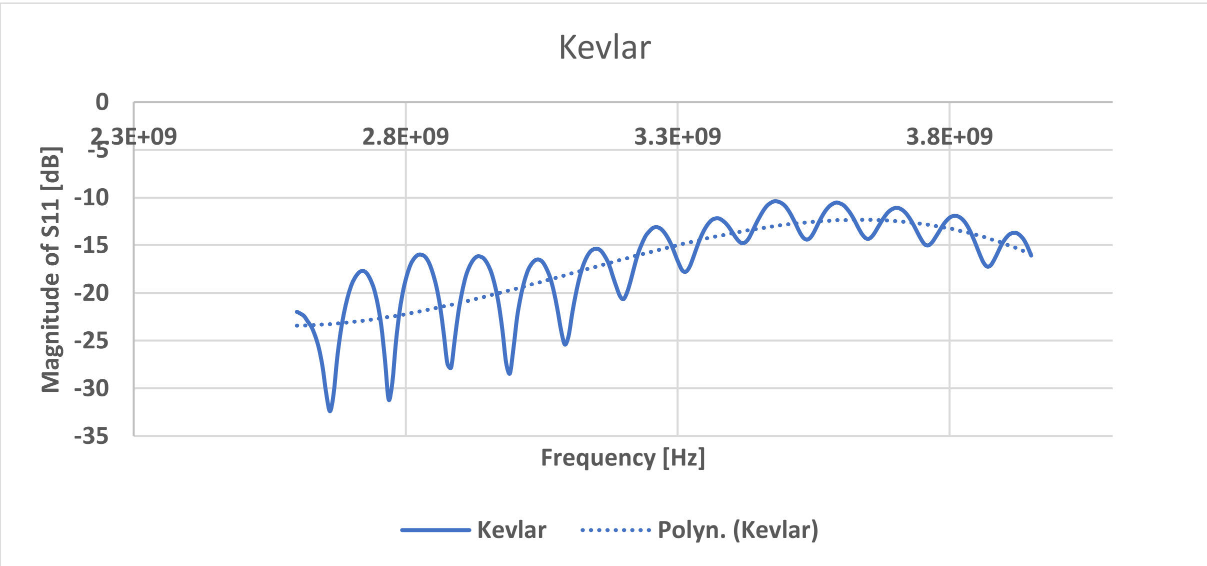

Figure 34: Results of S11 for Kevlar

Another figure 34 represents results for magnitude of reflection coefficient S11 [dB] over the same frequency as the previous experiment results. We can see that values are not close to 0 dB indicating that the material does not have good reflection properties. The blocking or shielding capabilities of Kevlar are poor and most of the electromagnetic wave is transmitted through the specimen.

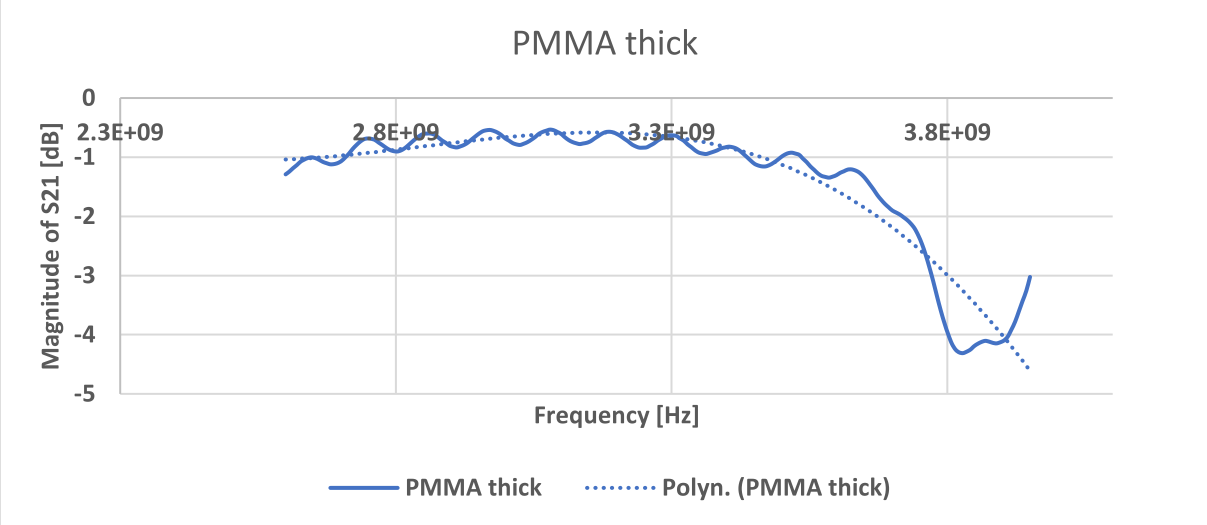

Figure 35: Results of S21 for PMMA thick specimen

Figure 35 represents magnitudes of S21 transmission coefficient in dB for PMMA material specimen with thickness of 3 mm. We can see that material is capable to allow signal to be passed through it while the minimal value is around -4.2 dB on frequency 3.8 GHz. The reason why we add polynomial function to the graph is to make a small prediction how the results for S21 would look like at lower frequency range where we were not able to do the experiments because we didn't have specific waveguides for it. This trend line with polynomial function of the third degree predicts that at the frequency range around 1 to 2 GHz, we could observe the magnitude of S21 could be between -0.5 to -1 dB. This would allow most of the signal to be transmitted through the material.

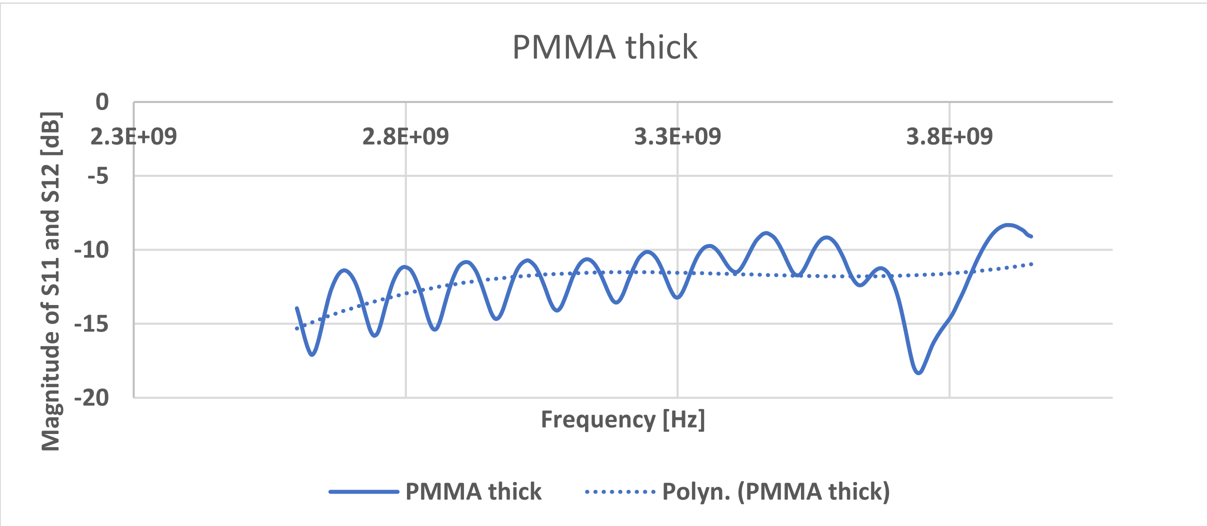

Figure 36: Results for S11 for PMMA

Now we take detailed look at the figure 37 where we compared results of magnitude of S21 for PMMA specimen with thickness of 3mm (blue line) and PMMA with thickness of 2 mm (green line) at frequency range 5.85 – 8.2 GHz. We can see that there is similar trend of the course. The noticeable results are in the second part of the graph, where the results for transmission of thin specimen are worse than for thick one. The thin specimen a bit different shade of the colour so there is the question of this could affect the final results.

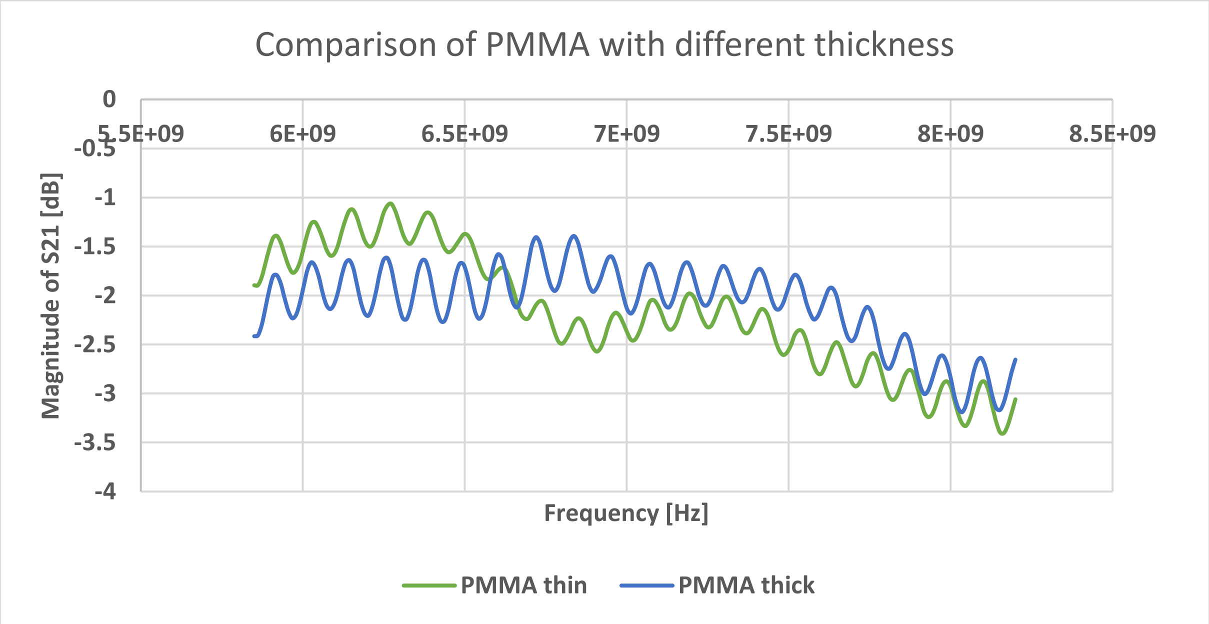

Figure 37: Comparison of S21 for PMMA with different thickness

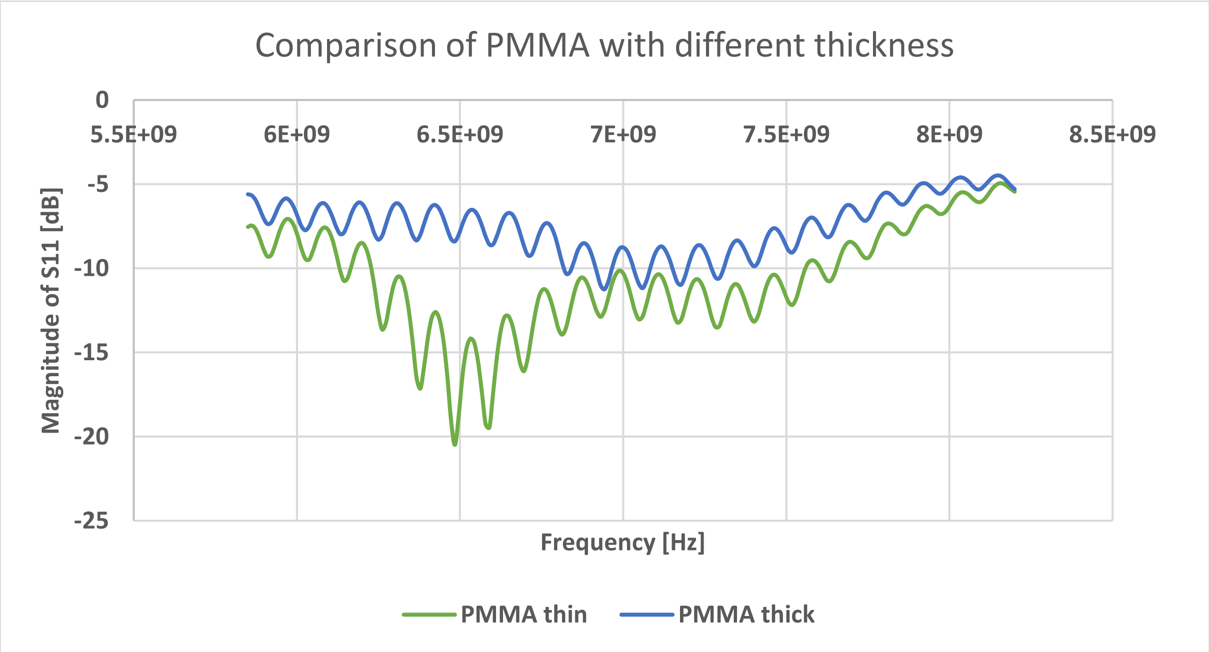

Figure 38: Comparison of S11 for PMMA of different thickness

In the figure 38, there are presented results for PMMA of different thickness for S11 reflection coefficient in dB over the same frequency range as the previous experiment results. Here we can see that the magnitude of reflection has its minimum with value -20 dB in frequency of 6.5 GHz while results for thicker specimen remain similar through the whole frequency range.

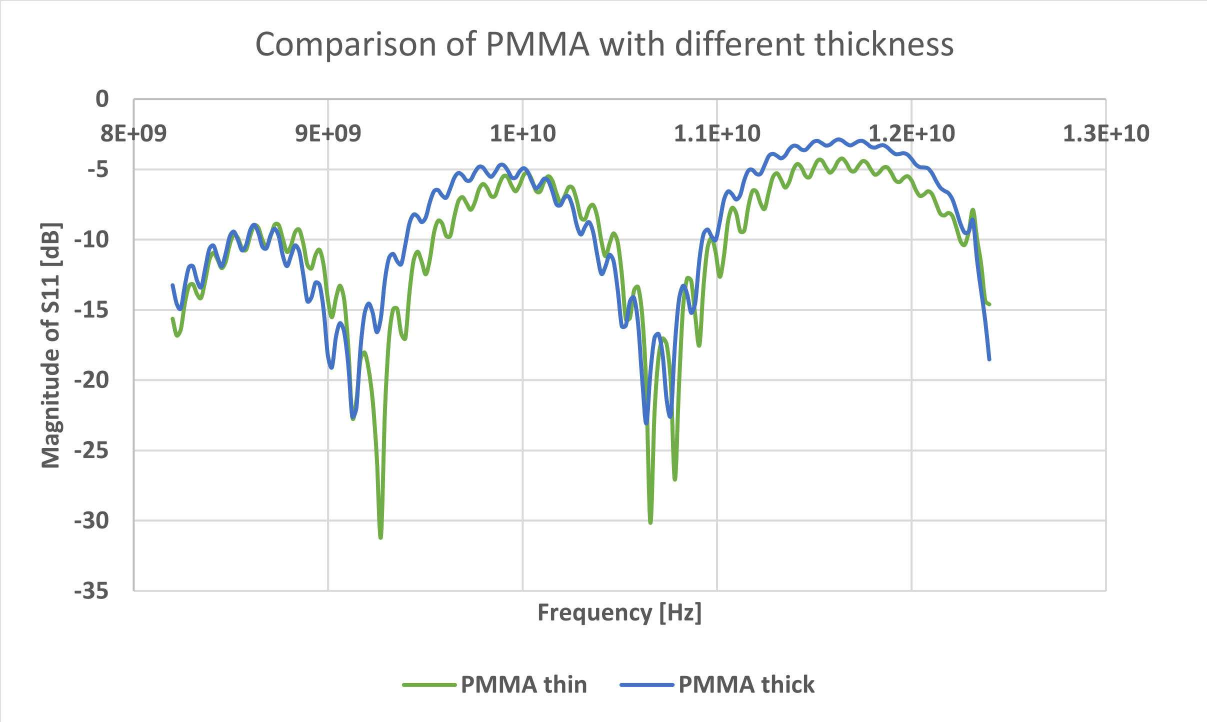

Figure 39: Comparison of PMMA specimens at higher frequencies

The last figure 39 shows results for PMMA specimens at frequency range 8.2 – 12.4 GHz where we measured magnitude of reflection coefficient S11 in dB. We can see repeated trend where measurements have their peaks with minimal values around -30 dB for thin specimen and -22 dB for thick specimen in frequencies 9.4 GHz and 1.07 GHz. There are different reasons how this could be created. First reason: material properties such as permittivity and permeability can cause that the electromagnetic wave may penetrate at different extents and create multiple reflection minima based on these interactions. The second reason is that every material has certain resonant frequencies that occur due to the material properties, thickness of specimen and measurement set up. When we observe dip in values it indicated that bigger part of the electromagnetic wave was absorbed.

3.1.3.2. Transmission, Reflection, and Absorption of the specimens

In this section, we discuss the evaluation of the measurements of the individual material specimens obtained from experimental part. Here, we focus on the key parameters of

Transmission, Reflection, and Absorption as they are crucial in determining overall signal propagation and shielding capabilities of materials.

Transmission (T) is the measurement of the amount of the electromagnetic signal being passed through the material specimen. This is a key parameter for evaluating the material's ability to be transparent for incoming signal. The value of this parameter is directly obtained from the VNA as a parameter S21.

Reflection (R) is a parameter for evaluating the amount of the electromagnetic signal that is reflected from the surface of the specimen. This parameter is important for applications where we want to reflect incident signals that could affect the overall performance, navigation, or communication of the system. The measure is derived from the S11 parameter that we can obtain from the VNA.

Absorption (A) quantifies the amount of electromagnetic energy being absorbed by the material specimen. It can be calculated as the addition into 1. We can use following equations:

$$A = 1 - R - T \tag{2}$$

$$T = |S_{12}|^2 = |S_{21}|^2 \tag{3}$$

$$R = |S_{11}|^2 \tag{4}$$

In the following figure, we present the electromagnetic waves and their simple mechanisms: transmission of signal through the specimen, reflection from the surface of the material specimen, and absorption that happens inside of the specimen and can be accompanied with internal reflection.

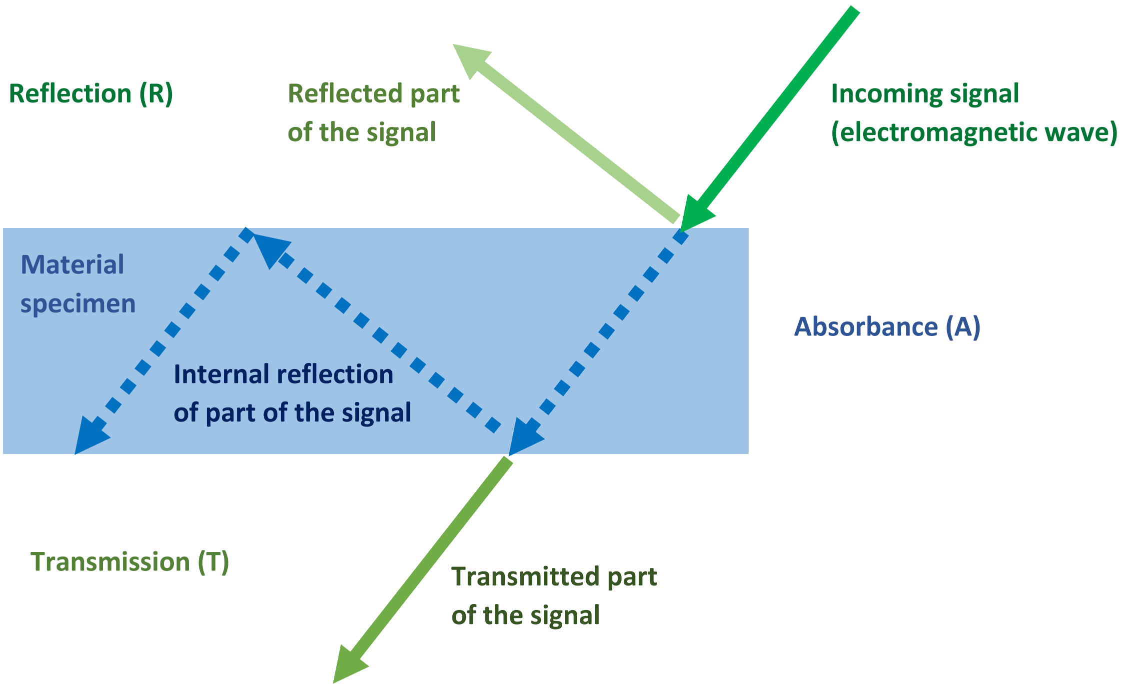

Figure 40: Mechanism behind EMI shielding

Calculations

In order to evaluate the values from experiments and show them as the following graphs, calculations with the following equations have been done to transfer values in dB into linear ratio.

$$x\,[dB] = 10 \cdot \log_{10}\left(\frac{P_1}{P_2}\right) \tag{5}$$

$$a = \left(\frac{P_1}{P_2}\right) \tag{6}$$

$$a = 10^{\left(\frac{x\,[dB]}{10}\right)} \tag{7}$$

Aluminium alloy specimen with thickness 0.4 mm

Results for thin Aluminium alloy indicated that it exhibits very high reflection across all four tested frequency ranges. This material specimen has very poor transmission properties suggesting that it is not good choice to be utilized as an efficient transmitter of electromagnetic signals. Transmission of electromagnetic waves is low that it is not even recognizable from the following graph. And additionally, its high signal reflection may cause interference with other communication systems.

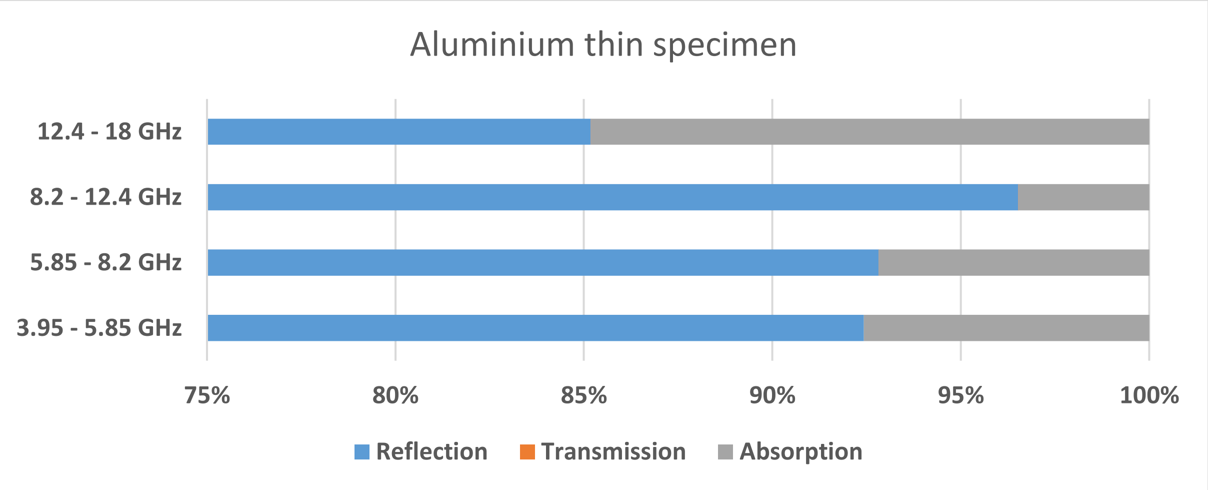

Figure 41: Energetic balance of thin Al specimen at different frequencies

Aluminium alloy specimen with thickness 2 mm

We had only one specimen of aluminium alloy with bigger thickness of 2 mm so we can compare the results only at one frequency range with thin aluminium alloy specimen, but it seems like enough at this point as we can already see differences in the following graph. We are working with results from tests at frequency range 3.95 GHz – 5.85 GHz. Specimen with thickness 0.4 mm allows bigger part of the signal being reflected from the material. And still we can see that the results for transmission coefficient are very poor and aluminium alloys are not suitable for applications where the signal integrity is critical even if we create the component from very thin sheet of material.

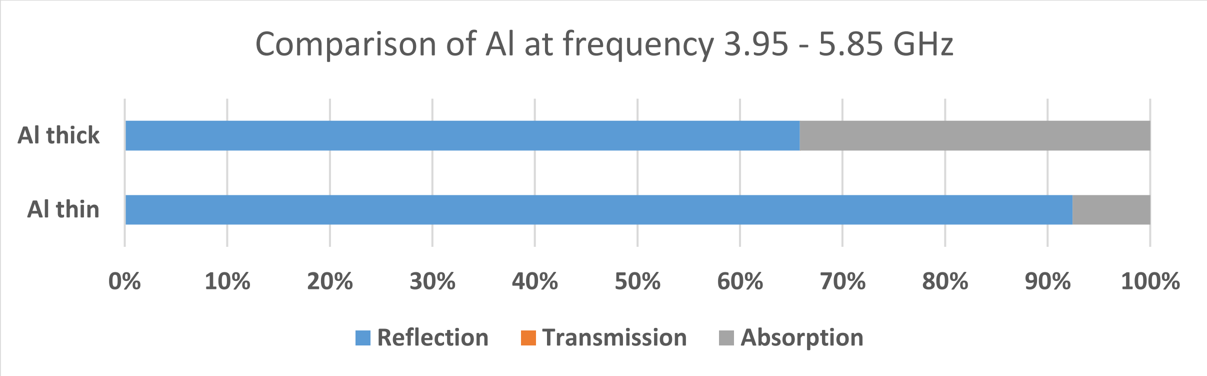

Figure 42: Energetic balance of Al specimens with different thickness at the same frequency

Carbon fibre composite specimen with thickness 1 mm

We can see another material that is not suitable for applications where transmission of the signal is necessary. Despite its superior mechanical properties, Carbon fibre composite's reflection is so high across all tested frequency ranges that it is making it inappropriate for the cover of the drone.

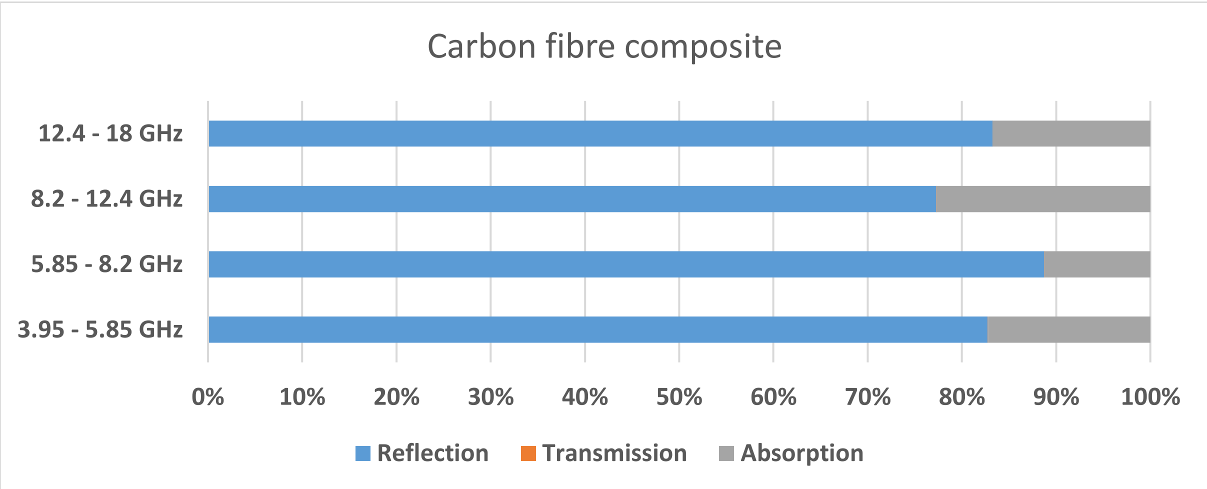

Figure 43: Energetic balance of carbon fibre composite specimen across different frequencies

Copper specimen with thickness 2.5 mm

Another metal specimen where results met expectations. Copper is known for its high electrical conductivity. Material reflected a substantial portion of signals, and another big part of them is absorbed. And interestingly, value of the transmission got so low that it is not even visibly seen in the graph presenting energetic balance. Absorption of this material is high, similarly as in previous material specimens. This confirms that copper is an excellent choice of material if we need to use it in applications where we require more of shielding and blocking of the electromagnetic signal.

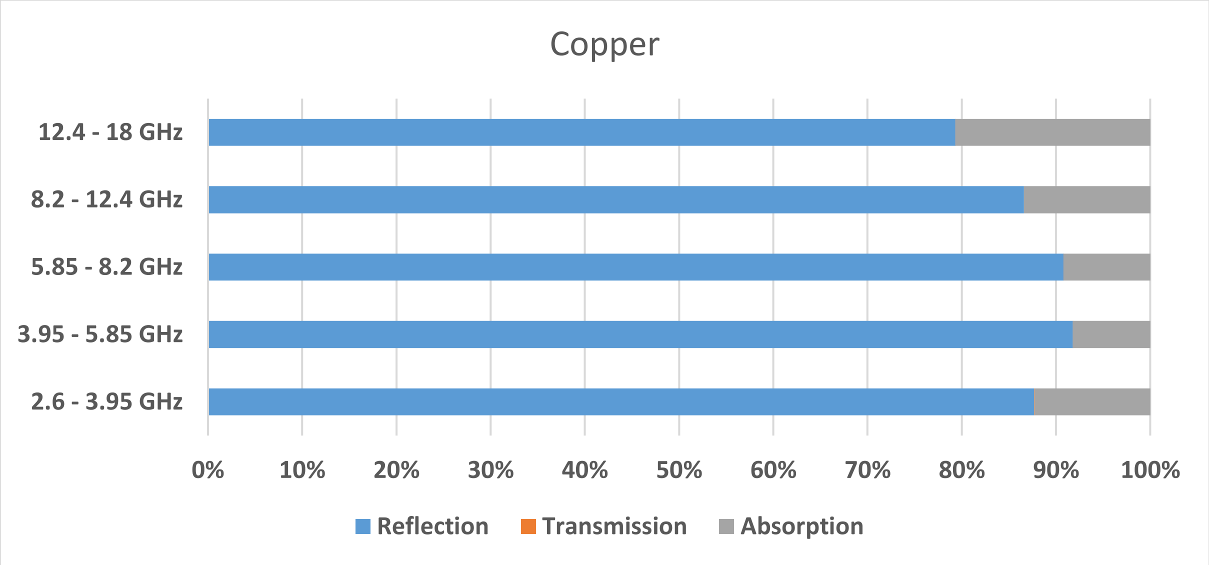

Figure 44: Energetic balance of copper specimen

Interglass specimen with thickness 2.8 mm

Interglass specimen that was utilized as a representative of glass fibre composites shows a good balance between mechanical properties and electromagnetic performance. Reflection properties are quite moderate in comparison to previous materials. But the reflection coefficient seems to have higher value with the raising frequency. The transmission is high in the selected range of frequencies proving that it effectively allows signal passage.

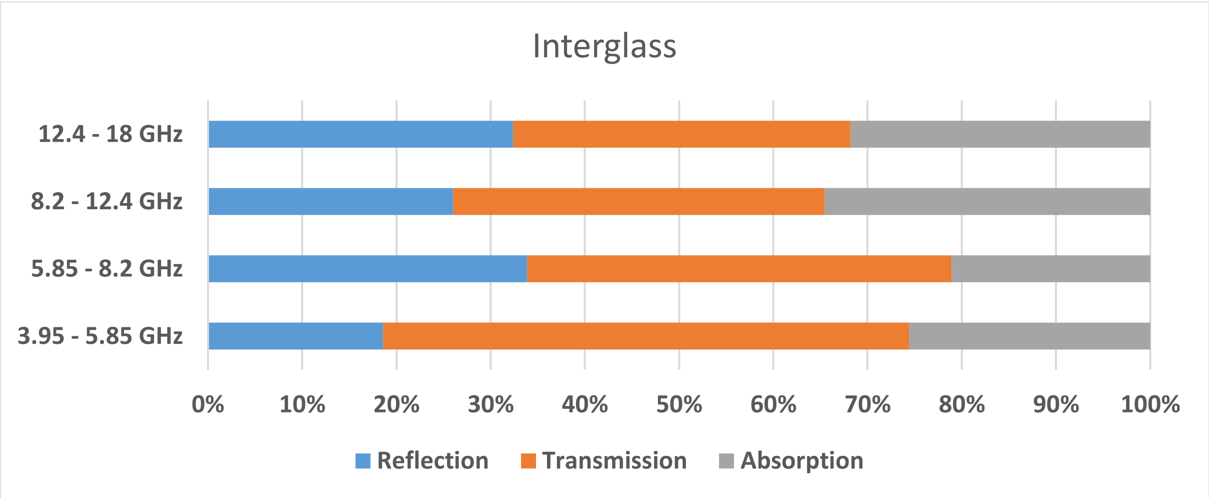

Figure 45: Energetic balance of the representative of fibre glass

Kevlar specimen with thickness 0.5 mm

The transmission for Kevlar specimen is high for most of the frequencies, while reflection portion is very low, indicating minimal reflection of electromagnetic waves. There is an interesting trend between different frequencies, where transmitted part of the signal got smaller with growing frequency. These results can happen because some materials are more sensitive for transmission of signal on specific frequencies while on the rest of the frequency range, the transmission can result in great values. This material provides a good compromise between signal transmission and strength.

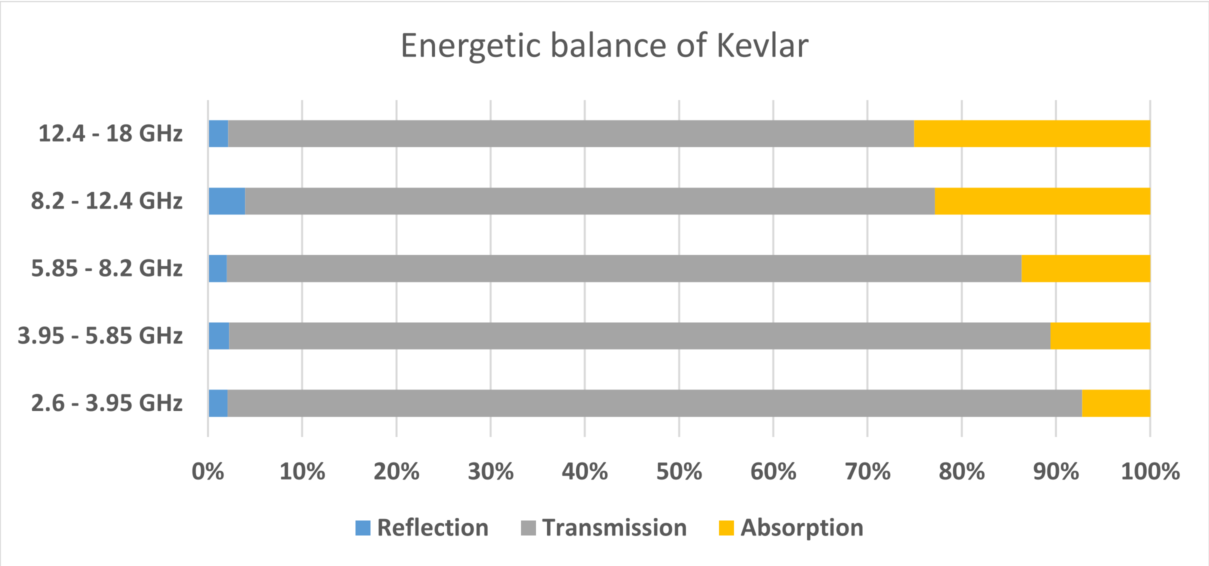

Figure 46: Energetic balance of Kevlar specimen

PMMA specimen with thickness 2 mm

PMMA specimen exhibited low reflection properties across three frequency ranges indicating that a very small part of the signal was reflected, but not as small as in case of Kevlar specimen. These low reflections ensure minimal interference with other systems e.g., navigation and communication. The transmission is very high and comparable with the results of experiments with Kevlar, concluding it effectively allows signal passage.

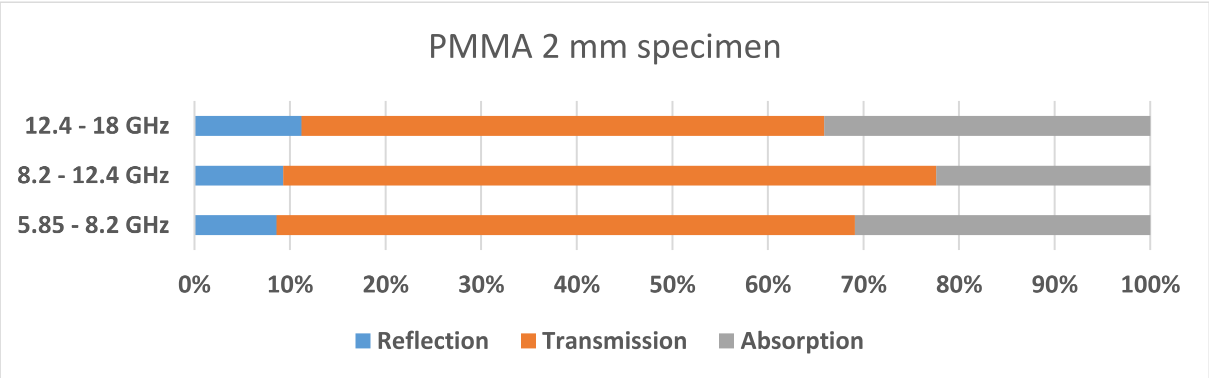

Figure 47: Energetic balance of thin PMMA specimen

PMMA specimen with thickness 3 mm

Luckily, we were able to get another PMMA specimen, but with different thickness. This specimen allowed us to see results at smaller frequency ranges which shows the second-best signal transmission properties among the tested material specimens while coupled with very low reflection properties. Reflection coefficient gained bigger values with growing frequency, but for us the most important frequencies are the lowest ones. Overall, PMMA has favourable signal transmission and reflection properties meaning that in use of some application, this material will not cause dramatic changes affecting communication or navigation systems and it will ensure the operational efficiency and reliability.

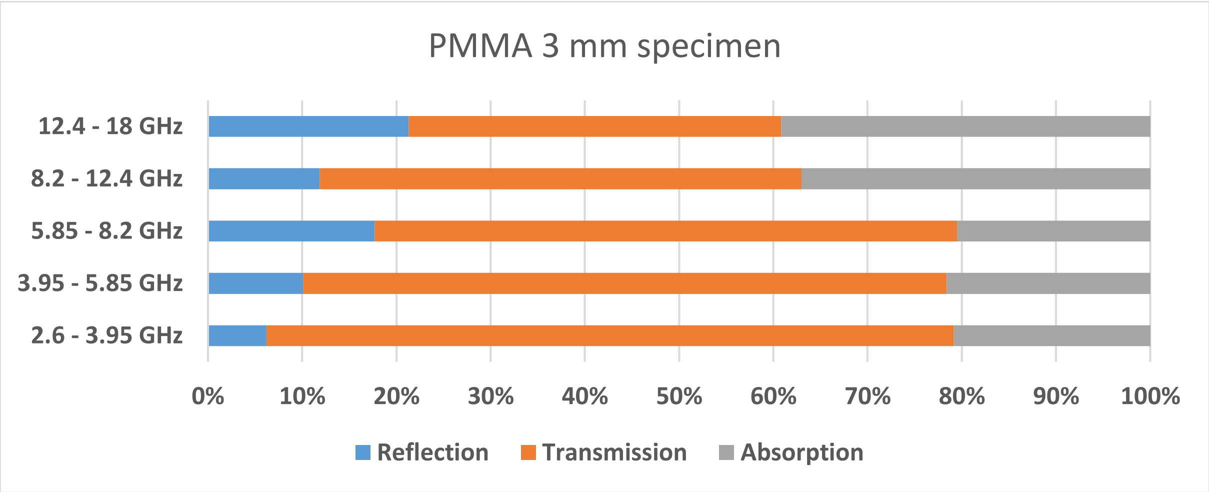

Figure 48: Energetic balance of thick PMMA specimen

For comparison, we represent results of PMMA measurements of two different thicknesses at two different frequency ranges. We can see the transmission of the signal stays similar with thickness difference of 1 mm. Absorption properties slightly grow with higher frequency and bigger thickness of specimen.

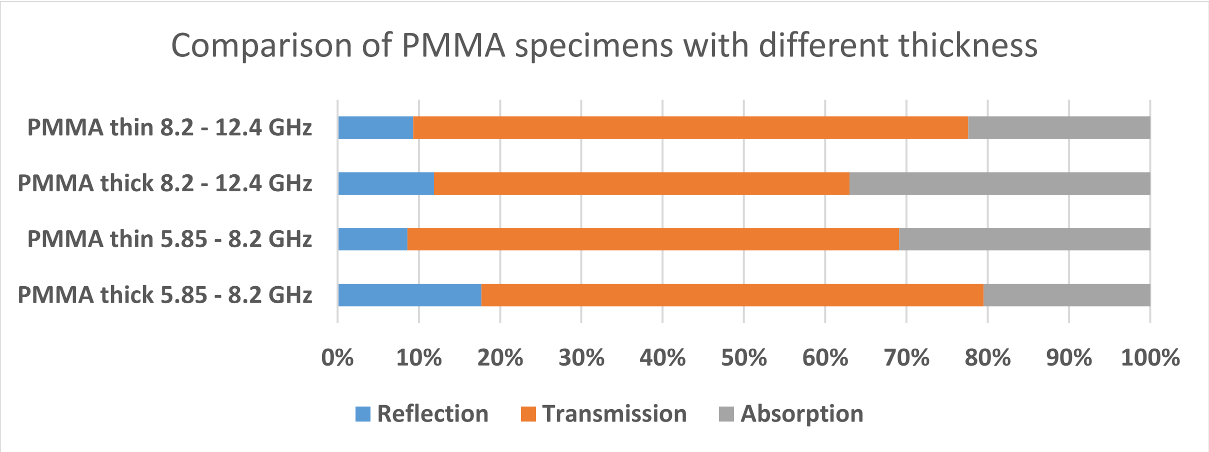

Figure 49: Comparison of energetic balance of 2 PMMA specimens

3.1.3.3. Shielding efficiency

In order to evaluate the measured values and present them as the following graphs, calculations with equations have been done. Shielding efficiency (SE) of material is presented with the following equations, where the equation consist of values for individual mechanisms:

$$SE = SE_T + SE_R + SE_A \tag{8}$$

$$SE_T = 10 \cdot \log_{10}\left(\frac{1}{T}\right) = 10 \cdot \log_{10}\left(\frac{1}{|S_{21}|^2}\right) \tag{9}$$

$$SE_R = 10 \cdot \log_{10}\left(\frac{1}{1-R}\right) = 10 \cdot \log_{10}\left(\frac{1}{1-|S_{11}|^2}\right) \tag{10}$$

$$SE_A = 10 \cdot \log_{10}\left(\frac{1-R}{T}\right) = 10 \cdot \log_{10}\left(\frac{1-|S_{11}|^2}{|S_{21}|^2}\right) \tag{11}$$

In this section, we present only few results in graphs of selected material specimens as the topic is more complicated for calculations. In the following figure, the results of shielding efficiency in % for PMMA with thickness 3 mm at the frequency range 2.5-4 GHz is shown. The values are oscillating around 40% as the shielding efficiency consists mainly of values for reflection and absorption that is lower for this material when compared to metals or some composites. It is because main part of the electromagnetic wave is being transmitted.

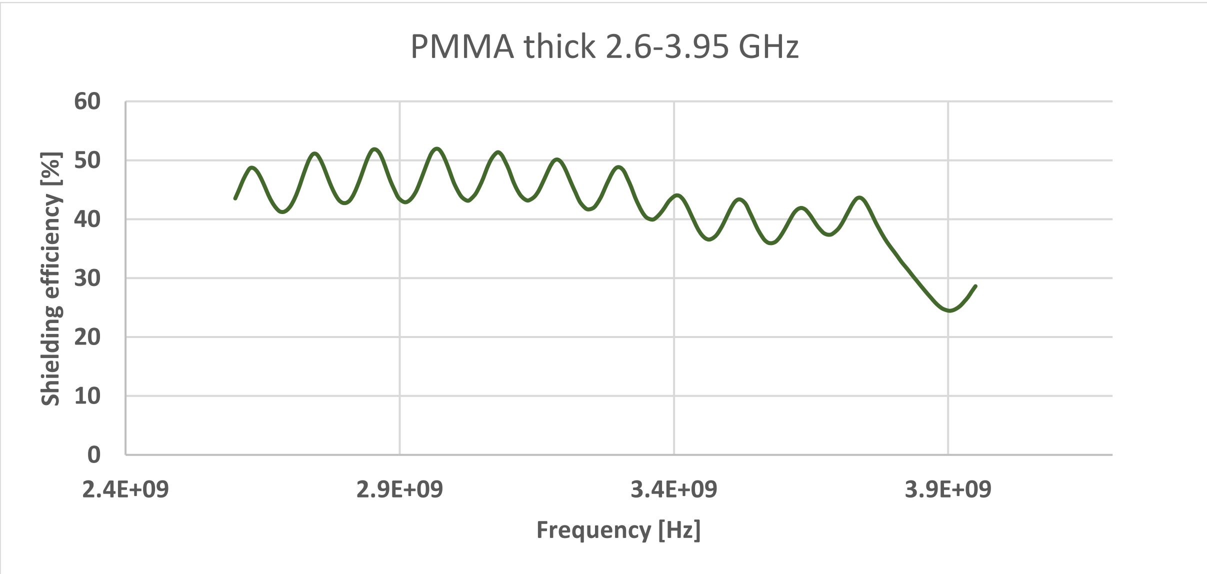

Figure 50: SE for PMMA 3 mm at 2.6 – 3.95 GHz

Another figure 51 represents results for thin PMMA specimen with thickness 2 mm at frequency range around 6 to 8 GHz to compare them with figure showing results from previous measurements. Here, we can see that shielding efficiency is lower and the value is reduced with the higher frequencies, where we got values around 20% of SE.

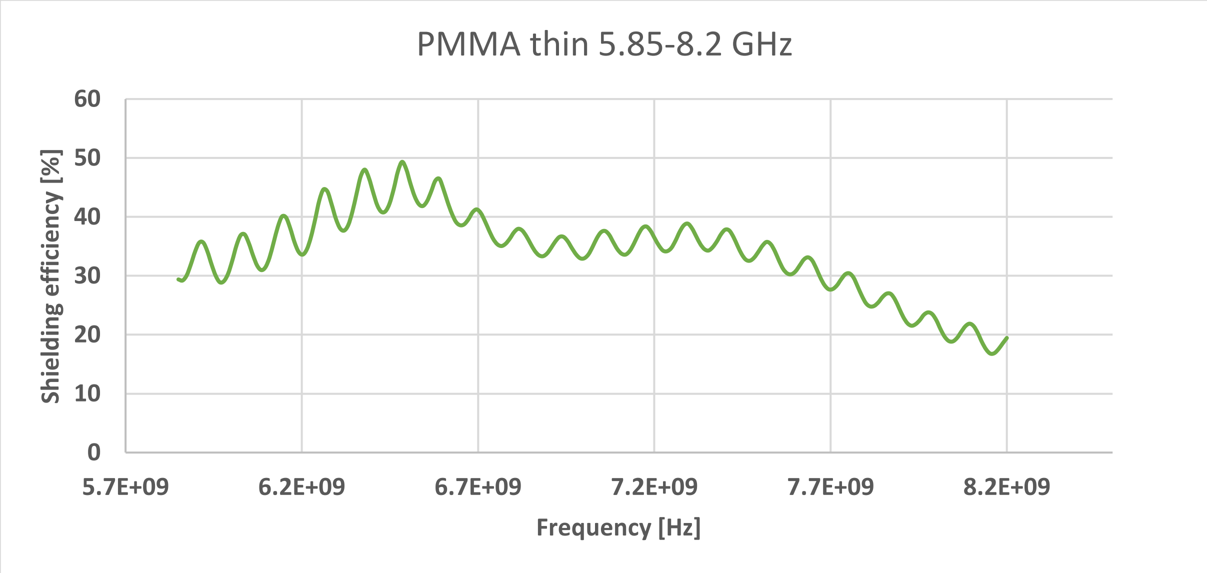

Figure 51: SE for thin PMMA at 5.82 – 8.2 GHz

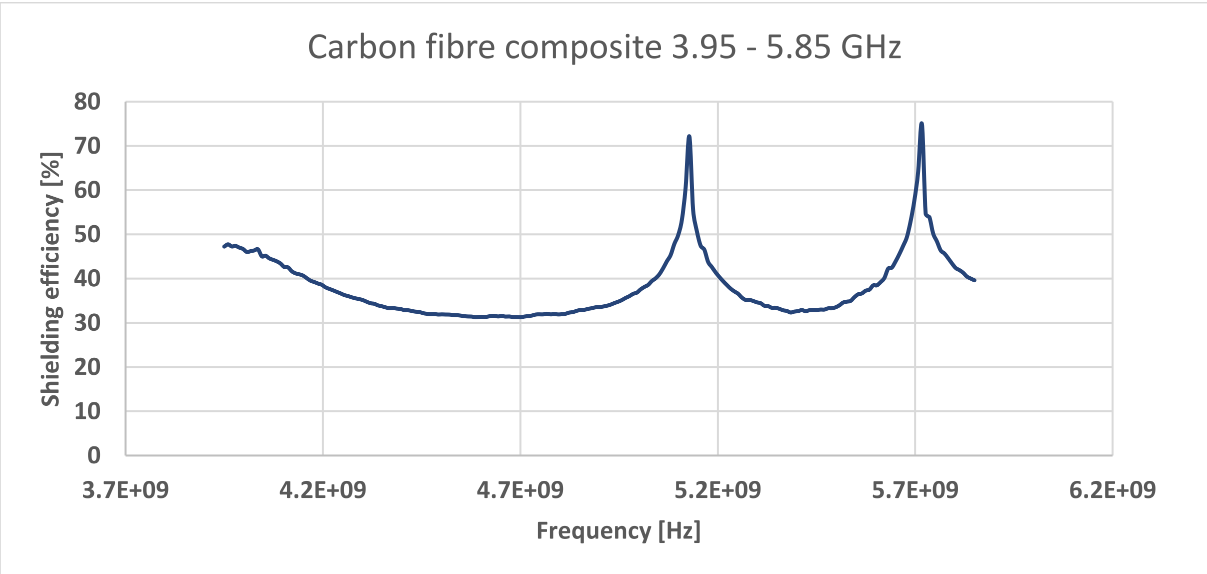

Figure 52: SE for Carbon fibre composite

Figure 52 reveals that there has been a steep rise in the values of Shielding efficiency around 2 different frequencies – 5.1 GHz and 5.7 GHz that stand out in the steady course of the values between 32-40 %.

3.1.4. Findings and discussion

In our project, we tested eight different specimens across five frequency ranges in order to evaluate their electromagnetic properties. The primary objective was to determine how samples interact with electromagnetic waves – if they reflect, transmit or absorb incoming signals. To achieve reliable results, we utilized waveguides as the testing equipment as they are ideal for such an experiment allowing us to measure the response through the material samples. Let's see what key findings for each material are.

Carbon fibre composite

Carbon fibre composites are widely utilized for their lightweight properties and strength. This material was used in several covers and components of the drones e.g., from company DJI. Our analysis showed that there has been a steady reflection coefficient with values between -0.6 to 8 dB indicating quite great ability to reflect incoming signals. The transmission values show that the material allows some transmission, but a significant portion of the electromagnetic waves is attenuated. The presence of peaks in shielding efficiency suggest that material's properties or internal structure can affect communication systems in some applications.

Copper and Aluminium alloy

Copper exhibited significant reflection and minimal transmission across all the tested frequencies together with another metal specimens – Aluminium alloy with two different thicknesses 0.4 mm and 2 mm. None of these specimens had massive peaks at some of the selected frequencies in terms of transmission and reflection and values stayed quite steady. S21 is consistent within range -80 to -95 dB and values for S11 were ranging from -0.5 to 4 dB.

Interglass, Kevlar and PMMA

Three materials selected in the research part of the project were analysed to understand their electromagnetic behaviour. All of them can be highlighted for their suitability for applications where transmission of the signals is important for the applications. These materials can be presented with minimal electromagnetic interference, and after the big portion of the electromagnetic waves was transferred through the material, another portion was slightly absorbed rather than reflected.

The overall results from our experiments with the Vector Network Analyzer and waveguides of different sizes revealed differences in how each specimen interacts with electromagnetic waves across various frequencies ranging from 2.6 to 18 GHz. By leveraging the strengths of each material and the insights from the experimental part we could make the final selection of the material for the cover design proposal that is presented in the following phase of our project. As stated earlier, the selection of the material has to be driven by several criteria: manufacturability, weather resistance, low cost, and lightweight properties.

After careful consideration and several tests, the overall winner became PMMA – a cost-effective material with efficient production style and after the experimental part, we can conclude that it is a smart choice for drone cover as it can allow signal transmission with minimal part being reflected and absorbed.

On the second position, we choose to place a Fibre glass. Material with best cost performance, moisture resistance and UV resistance, and pleasant manufacturing process. Its transparency abilities are lower than in case of PMMA but still advantageous for certain applications including our cover for the drone.

The third place was given to Kevlar. This material has highest transmission capabilities so it should actually be selected as a first choice, but there are a lot of disadvantages: The cost of manufacturing is very high and manufacturing itself is also very problematic since it is challenging to process and cut the material. Another unfavourable fact is poor resistance to UV, and it can absorb water which is even bigger problem for us. If we would use the material for the production of the cover of the drone, the cover would get soaked with water during rain which could lead to damaged electronics systems in the internal part of the drone.

Final discussion is devoted to Carbon fibre composite because this material is utilized in several drones not only for structural parts but also for both top and bottom covers. Such cover disrupts signal propagation and as an outcome, the communication and navigation systems won't work with good accuracy, reliability, and reassurance. After our comprehensive research and experiments, we can state that we do not recommend utilizing carbon fibre composite as a material for covers of UAVs and similar applications, where precise navigation is needed.

3.2. Design proposal

Designing a drone cover is a process that balances aesthetics, functionality, and durability. In this chapter, we will explore the design proposal by taking steps from initial concept to the final one that will be selected as a winner for the actual product. The designing process already began in previous chapters with a thorough understanding of requirements for the cover and with the wide research about already utilized covers at other drones with several different purposes.

In the following subsections, we will present a range of ideas for design that could be manufactured with selected material after the experimental part. The criteria should not be based only on material selection and performance, but also ease of manufacturing, cost-effectiveness, and impact on aerodynamics properties of the drone. Hopefully, the final design will reflect an optimal balance of various design proposals considered and embody the most effective solution. The selected design of the cover of the drone will serve as the foundation for the final product.

3.2.1. Designing process

Designing the cover is a process that involves several stages with the final goal to develop an efficient solution. In this chapter, we highlight the creation of multiple variations of the design followed by the selection of the optimal one.

Not every design parameter arises solely from technical or mathematical calculations and procedures. Some parameters of drones are determined through a selection process, requiring the mechanical engineer to be familiar with some decision-making procedures that involve understanding and the importance of making the best possible choice for the design.

The design process for most aircrafts and UAV-based systems can be broadly categorized into three main phases:

- The conceptual phase,
- The preliminary design phase,
- The detailed design phase.

3.2.1.1. Our drone

In this project, we are using the drone from FEE (the Faculty of Electrical Engineering) at CTU (Czech Technical University in Prague) that can be utilized for applications where the precision navigation and accurate positioning is necessary e.g., the inspection of constructions and buildings.

Key features of the drone include:

- Frame
    - The drone includes frame designed from the following materials: carbon fibre arms and Aluminium arm housing.
- Motor configuration
    - The drone features a powerful quadcopter motor configuration, with four high-efficiency motors, four ESCs (Electronic Speed Controllers) in an electronic circuit to control and regulate the speed of motors, and four propeller blades on propeller hubs and propeller mount base.
- Autopilot system
    - Equipped with autopilot system, the drone offers autonomous flight capabilities. It integrates a NUC (Next Unit of Computing) board used as a computer kit,

- Sensors
    - To enhance situational awareness and capabilities of obstacle avoidance, the Lidar (Light Detection And Ranging) is included to target object surfaces with laser.
- Electronics
    - Battery system
        - Large-capacity battery with a service connector and a connecting connector provides continuous power supply.
    - Antenna
        - The drone is equipped with advanced antenna Emlid Reach M2/M+ LoRa radio that facilitates reliable transmission of navigation and control signals, robust connectivity between the controller and the drone.

Figure 53: The model of the drone

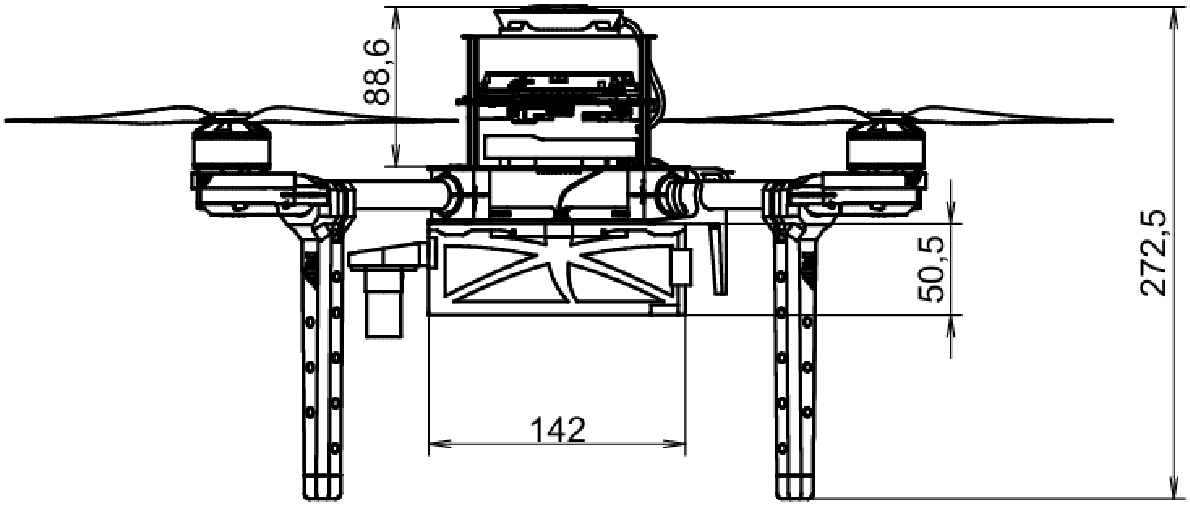

Figure 54: Side drawing of the drone

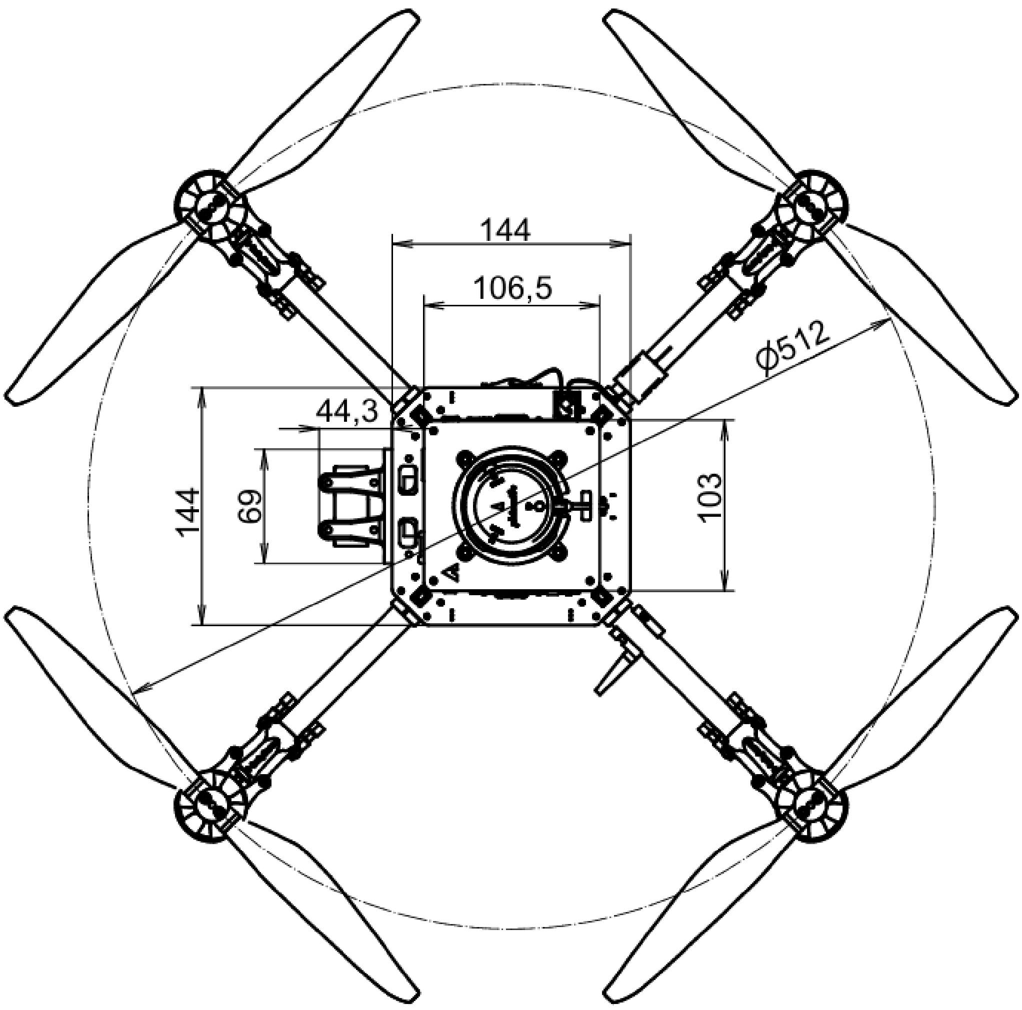

Figure 55: Top drawing of the drone

3.2.1.2. Design requirements

In developing phase, a set of requirements was discussed to try to make the final product meet the best performance, functionality, and durability. These requirements were utilized to guide us during the design process and served as important marks for evaluation of various concepts. The key requirements are outlined below:

- Aesthetics
- Shape and size
- Aerodynamics efficiency
- Producibility and ease of manufacturing phase and its cost

Other factors we can think of are cable management, ventilation, fastening mechanism, easy maintenance and accessibility, and disposability and life cycle.

In this chapter, we are not mentioning information and requirements related to material e.g., lightweight characteristics, material durability and strength etc. because the selected material already has its own properties.

3.2.1.3. The conceptual phase

This phase marks the beginning of the designing process in which we can evaluate initial ideas based on the previous research about drones and their cover and brainstorm with gathered information. During this journey, we involved thinking about fundamental requirements such as the need for impact protection, resistance to weather conditions e.g., rain, moisture, UV light, minimization of weight of the cover which affects whole drone, and aerodynamic efficiency. Sketches and basic models are used to visualize and communicate early ideas and changes in the proposed design.

Design idea 1:

Our first design concept is influenced by the capabilities of software Autodesk Fusion 360, a powerful modelling tool with simulation tools that offers creation of an optimized cover design. Fusion 360 is a cloud-based Computer-Aided Engineering (CAE) software and an innovative tool that allows for parameter optimization. It plays a significant role in achieving the balance between strategic weight reduction and enhanced structural integrity across various drone functionalities and elements.

Shape optimization refines the external geometry, including the outer boundaries of structures. This process adjusts grid locations while maintaining connectivity which remains unchanged. Models generated by utilizing this type of optimization are usually not manufacturable using conventional fabrication approaches e.g., stamping, casting, and forming. The additive manufacturing (AM) can create design with more complex geometries as it expands the flexibility of design freedom. The conducted generative study takes around 15 minutes; however, the final duration may vary based on the device specifications and equipment (e.g., size of the RAM, internal memory, processor, operating system), design type and complexity configurations.

The idea behind this structure at the following figure was to provide robust protection of internal components by having construction under the cover that find the optimal distribution of material within a defined space and enhance stronger protection against falls of the drone or potential bumps into a tree branch or building structures.

As we can see from the first picture, using special shapes and types of the structures for the inner part of the cover was also discussed. One of the structures was a Honeycomb - the hexagonal shape that evenly distributes forces and is often utilized in aerospace applications. Another idea was to try to use fractal-inspired structures that could help distribute stress, or even bio-inspired geometries and patterns that can offer insights into efficient load-bearing structures. One of the specific bio-inspired design is Voronoi Pattern – an irregular cellular structure that mimic patterns found in nature. For instance, there is a special app *Voronoi Sketch Generator* that was created way back already in 2015 and can be added into Autodesk Fusion 360 for generating Voronoi diagrams with several styles. And lastly, Foam Core Structures that can provide both, lightweight properties, and strength.

We later abandoned this design idea because it is rather complex and time-consuming.

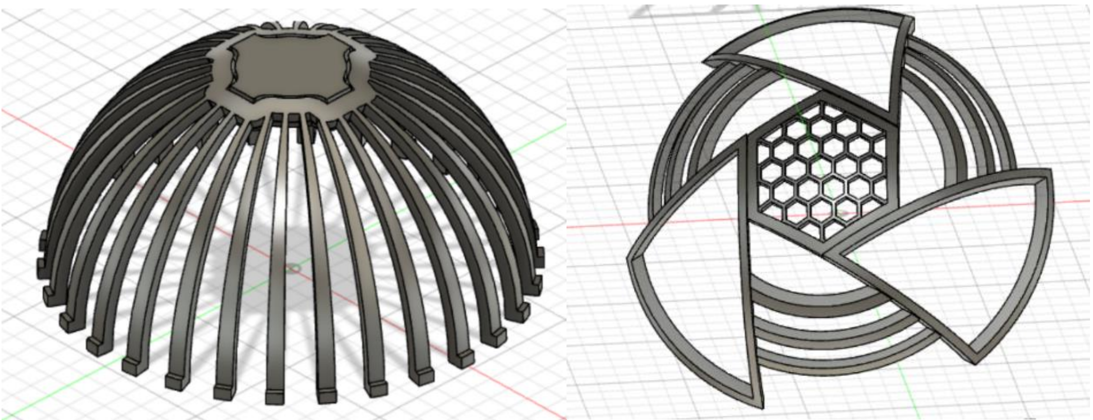

Figure 56: The first idea with reinforcement structure under the cover, and the later concept using honeycomb structure

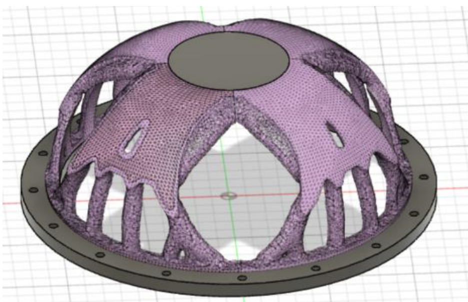

Figure 57: The initial concept where we used shape optimization in Fusion 360

Design idea 2:

The second design concept embraces more industrial approach to emphasize manufacturability. This idea features cleaner lines and reinforced sections.

The final conclusion was to not choose this concept and explore more options because it was not aesthetically pleasing for the author.

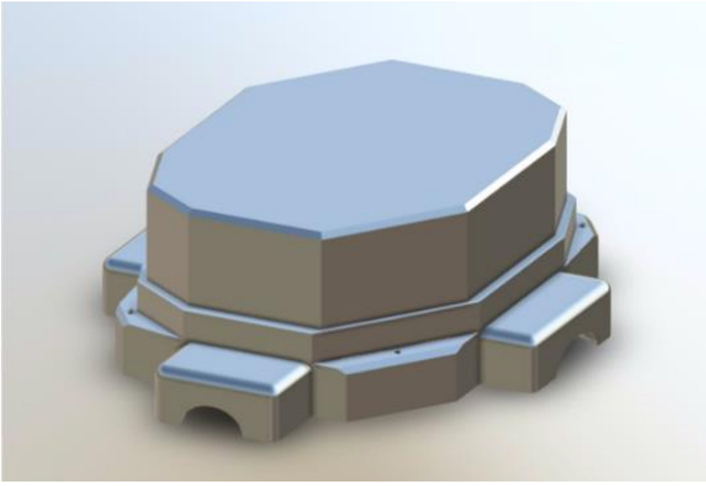

Figure 58: First industrial approach for the cover design

Design idea 3:

Our third concept again takes inspiration from natural forms as it results in design with smoothing and flowing shapes that are actually very popular on drones nowadays as these shapes are pleasing to the eye. This idea focuses on aesthetic appeal and compliments the drone fundamental construction with sleek design of the cover. The smooth surfaces also aid in reducing air resistance and enhance flight efficiency.

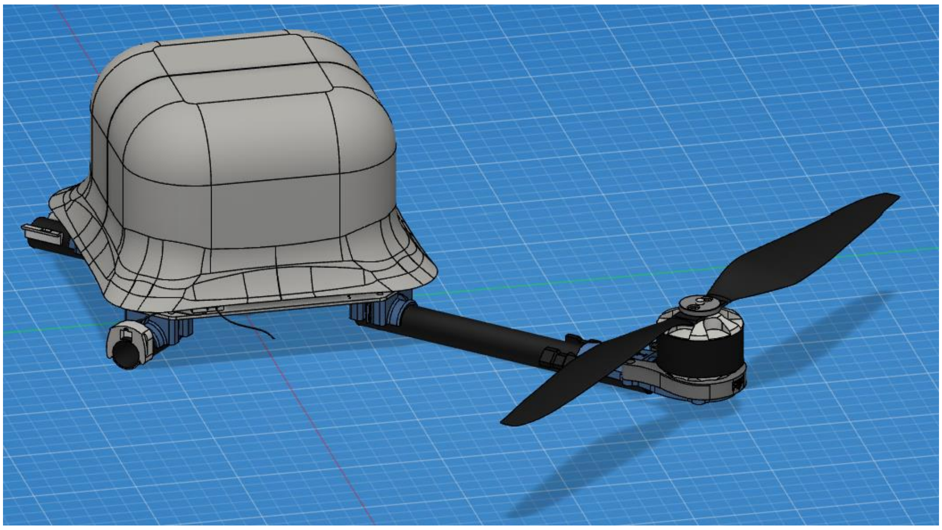

Figure 59: Model of the cover with visible lines

During this phase, we were allowed to explore a diverse range of shapes while thinking about the various requirements and challenges that we need to face when designing the cover e.g., enhanced flight performance, strong protection against encountering an obstacle, and weather conditions.

Final decision was made, and this became another design idea that was not selected. The reason behind it was that smooth surfaces are difficult for creation of drawings where we should include information about dimensions and the distance of the individual parts.

Figure 60: Design with smooth shapes

Design idea 4:

After the concept inspired from natural forms, we have developed one more design that emphasize clean lines and shapes but is closer to industrial style. With the fourth design we finally get closer to what we envisioned from the cover in terms of the aesthetic.

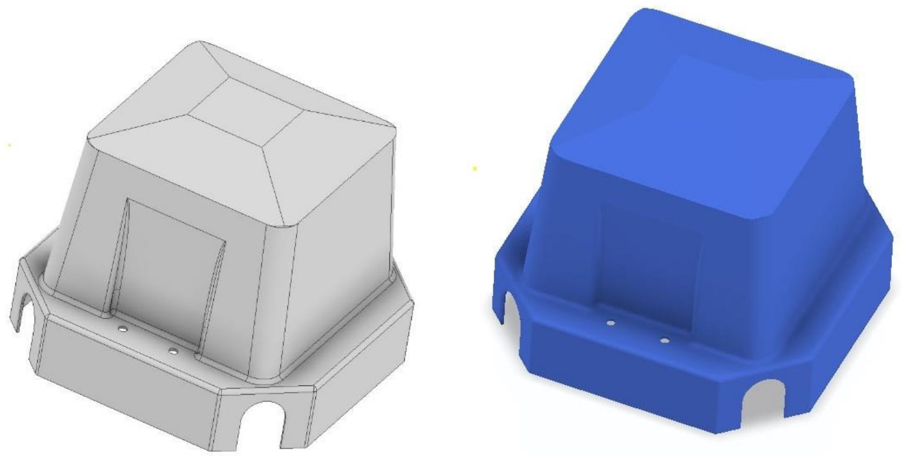

Figure 61: Additional design concept utilizing industrial style

The only disadvantage here was that the fourth design concept seems like it does not maintain the core objective of aerodynamics and there could be a problem with holes for fasteners placed too close to a body of the drone, meaning it would be more difficult during maintenance to take off the cover and put it back on the drone. This drawback will be solved in the following phase.

3.2.1.4. The preliminary design phase

In this stage, we developed more detailed representation of chosen concept. Then we explored different structural configurations in iterative phase and work with feedback loops that allowing us to continuously optimize and improve the design idea. Here, we include assessing feasibility, and think about whether the selected concept will have benefits and future.

After extensive development and evaluation of previous design ideas, we came up with a final concept for the cover of the drone that could meet set of criteria that were essential for performance and functionality. The final shape was created to balance practical functionality, weight distribution, manufacturability, aerodynamic performance, easy manoeuvrability during the flight with longer flight times, durability, and aesthetic appeal, so it incorporates few of flowing lines and smooth shapes on the edges. The concept is represented with this shape because we want it to match the contours of the drone's body to provide a snug fit.

Aerodynamic efficiency was one of a key consideration and with this cover we would like to minimize air resistance and drag. That's the reason why we don't have any bended parts inwards like in previous design. This concept should maintain stable flight in various conditions and to ensure that Computational Fluid Dynamics (CFD) simulations could be considered to conduct in order to evaluate airflow over the surface of the drone and contribution to energy efficiency.

To prevent damage to critical components, cause by encounters with obstacles such as building structures, tree branches etc., we created the design with both, top and bottom cover. Additionally, the rounded, smooth edges of the cover were proposed to help deflect the foreign object away from the body of the drone and ensure reliability in diverse operational environments.

The placement of fasteners was considered to ensure ease of assembly. There are two types of fasteners that can be utilized in this project. One of them are screws that can provide maximum support during unexpected encounters with obstacles and keep the drone cover in place. Such fasteners should be made from corrosion-resistant material to maintain long-term reliability while withstanding exposure to outside environment that can be sometimes very wet due to humidity, moisture, or rain. The other option is to use small magnets that would be hidden and glued in the same holes where screws could be placed. They are a compromise in aesthetics and aerodynamics. Also, they allow quick release of the cover if the drone body requires frequent access e.g., to electronics and batteries and enable trouble-free maintenance.

Lastly, two other aspects were considered to prioritize ease-of-use and practicality. It was cable managements and ventilation. Generally, drones include several cables that need channels to get them from internal components to other parts of the drone. To help prevent tangling we created hole in the bottom cover for battery cables that have female ending. The other cables are considered to stay inside of the drone to prevent damage. Then we considered incorporating ventilation holes to prevent overheating of the inside components and to make sure that the drone operates at optimal performance levels.

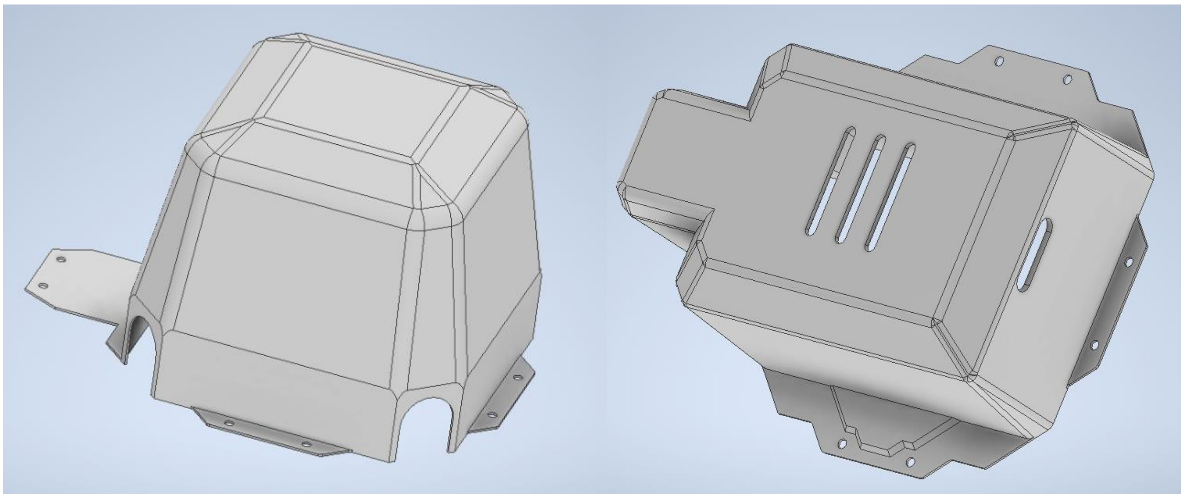

Figure 62: The final design of the top and bottom cover

3.2.1.5. The detailed design phase

This phase allows us to finalize the dimensions, and structural details of the cover. More detailed drawings can be created with specifications and guidance to manufacturing process. At this point we are considering manufacturability and cost to ensure that the final design can be produced efficiently and safely and reliably integrated into our drone.

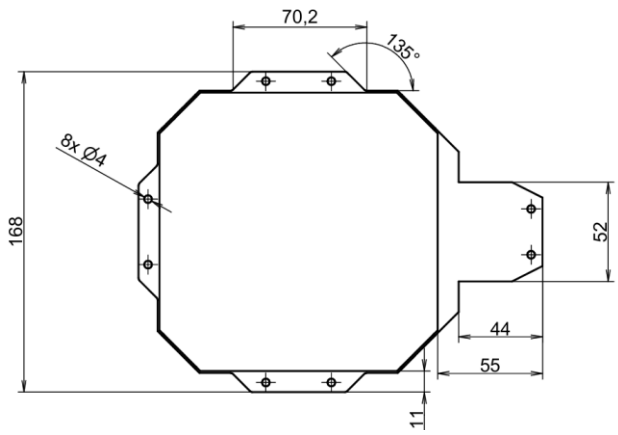

Figure 63: The top view drawing of the top cover

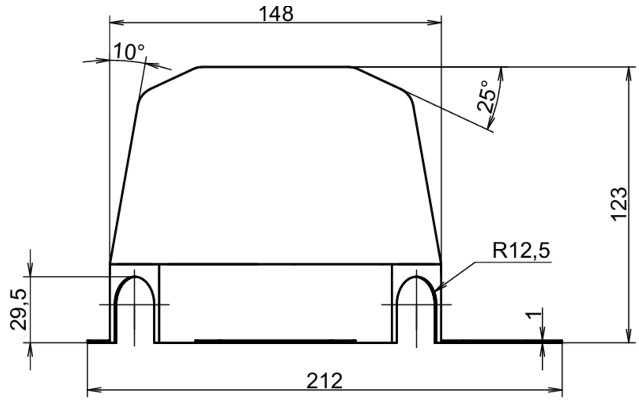

Figure 64: The side view drawing of the top cover

The cover is shaped to fit the drone's body and frame. A length of 212 mm, a width of 168 mm, and height of 123 mm of the fitting design of top cover, and height of 69 mm of bottom cover with same length and width ensures optimal functionality during flight. The overall height of the cover is 192 mm. The outcome of the optimal design is presented in figures 63 and 64: top view, and side view. Thickness of the cover is 2 mm.

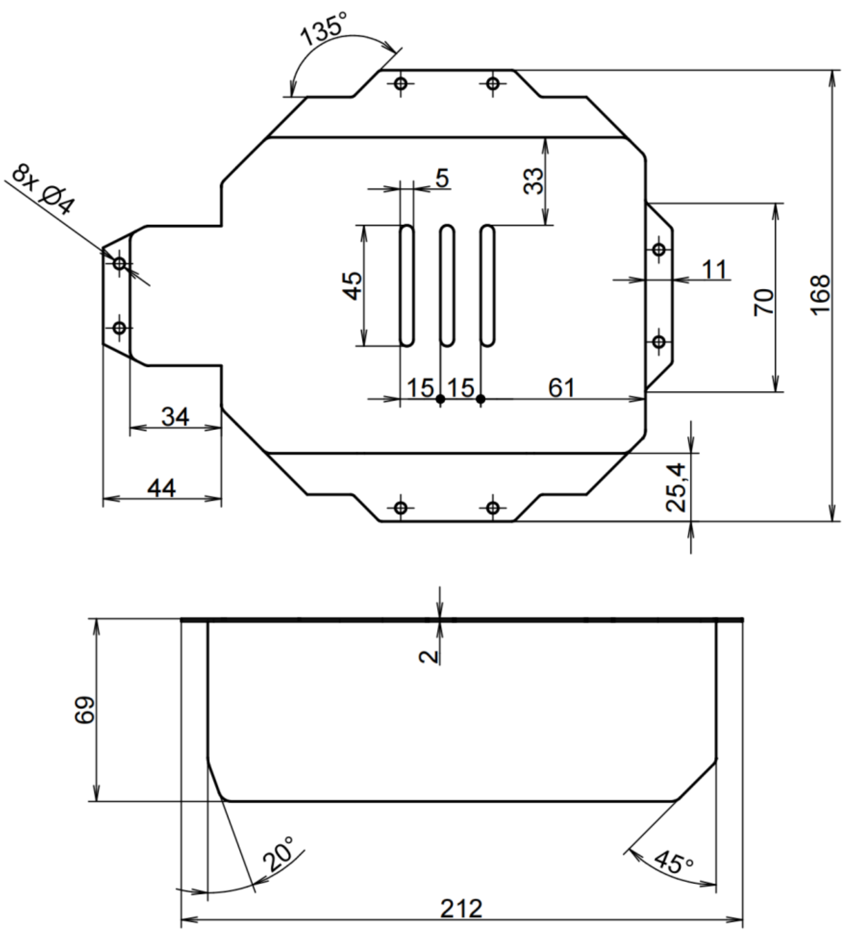

Figure 65: Drawing of the bottom cover

Figure 66: Drone with both covers

3.2.2. Manufacturing methods

We are at the end of acquisition phase that consists of preliminary design, detailed development, and production. And there are several design requirements: performance, stability, manufacturing, and cost. In the development of final product, an emphasis has to be placed on ease of manufacturing process and its cost-effectiveness. The chosen material is PMMA (followed by Fibre glass and Kevlar). This material offers and allows for various methods and each one of them is suitable for different design specifications. Fabrication technique utilized for processing can be injection moulding, thermal forming, or additive manufacturing.

Injection moulding is an efficient technique that has ability to produce complex shapes with high precision and with the rapid production at a relatively low cost which is ideal for manufacturing on potentially large-scale.

Thermal forming allows creation of durable but still lightweight components with great surface finish. With this method, we can heat sheets of material and then form them.

Additive manufacturing or 3D printing is also one of the choices, but this one could be used for the production of exemplary first trial product – prototype.

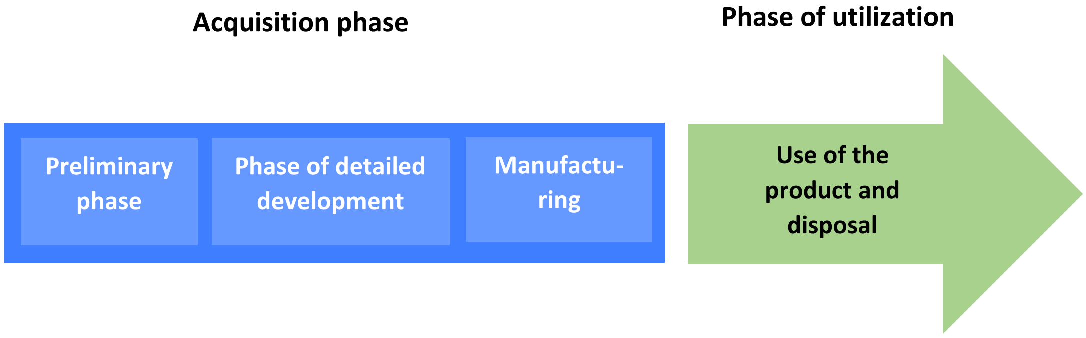

Figure 67: Life-cycle of the drone

The final cost is influenced by several factors, including production method, the scale of production and price of material. Since we are choosing to create the cover from only one material, the cost consideration does not need a breakdown into small sections.

As stated in research part, PMMA is a more affordable material than some other polymers and the cost-effectiveness is promised to be improved in the following years. Also, it is widely used in various industries making it easily available.

Injection moulding offers efficient production with minimal waste which reduces overall cost. The initial invest in equipment and tools can be significant, but over the large production these costs will be low.

Cost for potential customer will most likely be low in terms of the firstly buying the product, and for the following maintenance too. PMMA is already utilized for canopies, windows and similar products. This ensured us that the material is resistant to environmental factors and is very durable which can be translated into the fact that the maintenance cost will be very low and a lifespan of the product – our cover for the drone – will be long. Also, the durability further enhances the effective and reliable protection of internal parts and electronics and reduces the need for replacements in frequent time.

We also decided to shortly evaluate the potential use of glass fibre. This material would allow us to manufacture the final product through a lamination process that involves layering fine fibres and mix them with a polymer resin. The cost of raw materials (fibres and resin) is higher, especially when used in composites. But the initial investment does not require expensive tooling. The lamination process is slower compared to injection moulding and often requires skilled labour which can make the cost per unit increase and is not suitable for larger productions.

3.3. Conclusion

In this analytical part of the project, we conducted comprehensive experiments while using waveguides together with Vector Network Analyzer and then we continued with the evaluation of the results. The measured coefficients were transmission S21 and reflection S11, then we calculated the missing part of absorption. We not only evaluated graphs with measurement results but also made comparison of each portion of the mechanism – absorption (A), transmission (T), and reflection (R) for every material and tested frequency range and then we show few results for Shielding efficiency (SE [%]) of selected materials. The tests were crucial in determining the most suitable material that could be potentially utilized for the production of our drone cover while ensuring optimal durability, performance and cost-efficiency.

From the tested materials, we can draw the conclusion that the ideal candidate is PMMA with lightweight characteristics, efficient production method and low cost. The material demonstrated nice balance between mechanical properties and transmission characteristics allowing electromagnetic waves to pass through it with minimal interference – a crucial factor for navigation and communication systems of the UAVs. The second choice is fibre glass that had a bit worse results in experimental part. But the properties of the material, high availability in different patterns, good cost performance and weather resistance (mainly to moisture and UV) makes this material a very good choice for use in production. The last option is Kevlar with the best transmission properties in tests, but overall evaluation has poor results as the material is costly, can absorb water, has poor UV resistance and in general is tough to process in manufacturing. We also tested carbon fibre composite because this material is often utilized for components of drones. The material is pleasant for production as it does not necessarily need special tooling and processes for fabrication purpose, but it is not a good choice in terms of transmission of electromagnetic waves.

Then we continued with design proposal where we tried to evaluate different ideas. For instance, we came up with solution to use bioinspired shapes and designs, but we did not continue with this one. The other options are to create design based on industry guidelines and standards and come up with custom solution. We choose the last one to create the top and bottom cover for exact dimensions of the drone to enhance operational efficiency, make the design easy for taking it off the body of the drone.

4. Summary and future recommendations

This diploma thesis successfully addressed the multifaceted challenge of designing a cover for a drone, choosing of suitable antenna, and selecting material after experimental tests while all the assigned tasks were completed. This project was divided into two main sections – research part and analytical part.

In the research part, we systematically evaluated different materials that could be utilized as a candidate for production of the cover of the drone. Main material options were composites represented by carbon fibre and glass fibre. Then we delved into polymers that emerged as a very suitable option e.g., ABS, PETG, PMMA, PLA, and PMP. We also considered utilizing materials that are used for construction of radomes e.g., PUR (polyurethan foam), and Polycarbonate (PC), to protect the antenna from the external environment with minimal impact to the antenna's performance. We decided to choose the materials for experimental part based on the criteria (manufacturability, weather resistance, cost, material density, and lastly availability in the workshop). After this selection, we received specimens of Carbon fibre composite, representative of fibre glass, Kevlar, and PMMA. And since we were also capable to get specimens of Aluminium alloy and copper that are widely utilized in drone's components, we decided to let them go under the test too.

After selection of materials, we conducted research on suitable antennas and choose the one that offers great performance and is costly effective. It is Emlid Reach M2/M+ LoRa radio. Otherwise, if we would not look at the price, the best performance and reliability is offered by antenna H-RTK F9P Rover Lite that provides accurate positioning data and costs around 370 € that could be pricy for many people.

For inspiration and evaluation of previous designs of drones and their cover, we made small research. Analysing earlier various models and their aspects helped us to gain some degree of understanding and guide the development of our current project. In order to create a drone cover, we tried to integrate smooth design while still staying in the range of industrial style. This optimization enhances structural integrity and aerodynamic of the drone.

Comprehensive experimental analysis that allowed us to study properties of selected material specimens highlighted the importance of high transmission coefficient S21 with low values of reflection coefficient S11. The best results were presented with Kevlar, the second place was received by PMMA, followed by glass fibre. But PMMA was identified as the optimal material for the drone cover because it is more affordable and easily manufactured when compared to Kevlar. Also, PMMA does not absorb moisture and water during high humidity or rainy days. For manufacturing, we selected additive manufacturing to produce prototype. Then we would follow with injection moulding – a method that is able to produce complex shapes at a low cost on a large scale.

Findings from our research and other valuable insights from our analytical part can be built upon in future projects and researches. One of the recommendations for the future project for other students, young professionals and scientists is to include a broader range of material specimens that could help to potentially discover materials with even better structural and electromagnetic properties. This group of materials could include ABS, PMP, PUR, PETG, another type of glass fibre or material mixtures.

In terms of design of the cover for UAVs, we would recommend including comprehensive CFD analysis to get the design with better functionality. Another option is to try to create cover with some interesting reinforcing structure in the inside of the cover to ensure better protection during impacts of the drone with external obstacles. These structures can include honeycomb or bio-inspired patterns and geometries. Also, we should not discard the idea that the cover can be made of more than one type of material. For instance, the outside part of the cover can be manufactured from one selected material, while reinforcing structures can be made of another material with different properties.

In conclusion, each step was planned with quite a lot of details and successfully executed, resulting in a functional final product. Results of this project can lay a strong foundation for future research and development efforts to build a high-performance UAVs.

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