INTRODUCTION TO ANTENNA PLACEMENT AND INSTALLATION

Thereza M. Macnamara BSc, MSc (London)
INTRODUCTION TO ANTENNA PLACEMENT AND INSTALLATION
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INTRODUCTION TO ANTENNA PLACEMENT AND INSTALLATION

Thereza M. Macnamara BSc, MSc (London)
This book is dedicated to my three granddaughters Shanti Jasmine (AKA Cheeky), Sophia Jane Zahra (AKA Softie) and Teya Mared (AKA Twinks) who will hopefully read it when they are older.
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About the Author

Thereza M. Macnamara attained her first degree in applied physics and her master’s degree in microwaves at London University. After two years of teaching physics up to Advanced level, she worked as a microwave engineer at G&E Bradley. She then worked as a research physicist for Morganite Research and Development before returning to work as a microwave engineer, working on a standard field facility, waveguide components, thermistor detectors, and calibration at Wayne-Kerr Laboratories, Flann Microwave Instruments and Bradley Electronics. After a short break to have a family, she returned to work as an examiner at the British Patent Office and lecturing in mathematics and physics whilst her children were growing up. She then took up a post as a senior RF engineer at ERA Technology, where she worked on antennas, feed networks and as an EMC engineer, before taking up the post of an electromagnetics specialist at BAE Systems where she worked for 17 years. Whilst at BAE Systems she worked in the R&D department and on Nimrod, Typhoon, Harrier, Tornado and Jaguar aircraft, and then became the technical coordinator of the EU funded research project IPAS (Installed Performance of Antennas on AeroStructures). Apart from many technical papers, she has also authored a reference book on EMC, entitled “Handbook of Antennas for EMC”.

Preface

This book has been written as a reference book in a tutorial style. Each chapter is designed to be fairly self-contained, and the reader does not to read through the chapters sequentially, although sections have been cross-referenced. The reader also does not have to read a chapter from the beginning in order to find the definition of a particular symbol, for instance, since the details of each symbol are given after each equation. Although this may seem repetitive to the reader reading the book from the beginning, this approach is invaluable to the reader seeking to refer to a particular topic, and not wishing to spend time looking up the meaning of symbols used in equations and formulas. Practical details are given and the use of mathematical equations is kept to a minimum since most engineers who prefer the mathematical approach will find an abundance of textbooks using Maxwell’s equations but will be unable to find simple explanations of the physical phenomena underlying the mathematics.

Where appropriate, reference to documents and books is given with the particular page or section number. This enables the reader to quickly access the particular topic, and the author considers this a welcome departure from references made to entire books, with the reader required to find the relevant section.

This book is intended as a background and reference book primarily for antenna and integration engineers involved in the integration of a single antenna or the entire antenna layout on the airframe of an air vehicle. However, the techniques could equally be applied to antennas on any structure such as a land or sea vehicle as well as spacecraft.

Engineers in other disciplines such as electromagnetic health/hazard (EMH), systems and aerodynamic engineers seeking specific or general information on aircraft antennas as well as those involved with measurement, certification and qualification phases will also find this book very useful. The treatment is essentially practical and even experienced antenna design engineers will find it very useful, since they may not be familiar with distortion of the antenna pattern when installed on an airframe. The pitfalls as well as the benefits of different sites on the fuselage of an aircraft are demonstrated by the use of measured radiation patterns.

The reader is expected to have attained an academic level of about undergraduate degree or Higher National Diploma (HND) standard or have had some practical experience as a systems, EMH or antenna engineer.

The book uses SI units throughout, and lists all the abbreviations and acronyms commonly used. SI units avoid the use of the solidus (forward slash or division sign) and instead the use of negative indices is recommended. However, the solidus is commonly used in some cases, and thus has been retained in these cases.
A large part of the material used in this book is based on Installed Performance of Antennas on AeroStructures (IPAS) and the production of this book is part of the exploitation plan for the European Union (EU) funded Project IPAS.

The radiation pattern of an antenna is distorted when it is installed on an airframe and the installed pattern is peculiar to each airframe. Thus the radiation pattern on one airframe is completely different from that on another airframe and the pattern is also dependent on the electrical dimensions (the dimension in terms of wavelengths) of the surface and the electrical distance of the antenna from obstacles.

Chapter 1 explains the main properties of electromagnetic waves as applied to antennas in a qualitative manner, and is useful for engineers not familiar with antennas or the jargon used.

Chapter 2 provides an overview of most common systems connected to antennas used on commercial and military aircraft, and outlines the salient points of the systems with regard to the antenna. It does not delve into any detail concerning the receiving and processing equipment.

Chapter 3 outlines the antenna siting process and the interfaces with the other disciplines, showing the trade-offs that must be considered and iterations usually required before arriving at the final antenna layout. It demonstrates the difficulty of obtaining the optimum layout due to its low priority compared with the aerodynamic considerations. It also shows some typical antenna layouts.

Chapter 4 shows how the interactions between waves of the same frequency (but with different amplitudes and phases) produce resultants of different amplitudes. This provides the reader with an understanding of the complex nature of installed antenna patterns. The chapter explains qualitatively the effect of obstacles, frequency, wings and the curved ground plane on the radiation pattern of an antenna on an aircraft, by demonstrating how the antenna pattern is affected with the change in frequency and at different positions on the fuselage.

Chapter 5 describes the most common antennas used on aircraft but does not elaborate on antenna theory. It also includes the effect of the electrical size of the ground plane on monopoles, comparison between the different types of spiral antennas, and the effect of the aperture illumination on the radiation pattern of aperture antennas.

Chapter 6 on RF interoperability is particularly pertinent to systems and will provide background information to systems engineers. This chapter is equally applicable to radiated emissions, sometimes undertaken as part of the EMH clearance programme. It also demonstrates the difficulty of predicting the coupling between antennas that are not within line of sight, and provides empirically derived values for antenna gains used in calculating the coupling. The derivations were developed after a measurement programme undertaken in IPAS.

Chapter 7 qualitatively describes the different software commonly used for predicting the radiation patterns of antennas on structures without delving into the mathematics used, so that the reader does not have to understand the complexities of Maxwell’s equations in order to understand the aspects of computational antenna modelling on structures. Work undertaken under the IPAS research project involved computational predictions and measurements on the same scaled models by different partners using their own in-house facilities so that direct comparisons could be obtained between the different codes, as well as between measured and predicted results. This has provided an unique comparison
between the different types of computational modelling software available, since nor-
mally predictions are only performed by each aircraft manufacturer with a single suite of
computational software and one set of measurements for each type of airframe.

Chapter 8 provides a basic understanding of the measurement sites for antenna pattern
measurements and for radiated emissions as well as practical details of measurements.
It discusses the trade-offs to be considered in the choice of a scaled model and gives a
qualitative description of near and far field facilities as well as compact ranges. Ground
and in-flight tests are also described and some results shown.

The final chapter contains reference data such as conversion tables, conductivities,
dielectric constants, conversion between dBm and watts, electrochemical electromotive
forces (EMFs), EM spectrum with frequency wavebands and wavelengths, common for-
mulas, the periodic table (listed alphabetically by symbol), preferred scientific prefixes
and definitions.

Every care has been taken in the preparation of the manuscript. However, the author
would appreciate any comments on the topics covered or errors in the text, be they
typographical, technical or factual.

Acknowledgements

I would like to thank Enrique Escolano, Jaco Verpoorte, Pat Foster, Harmen Schippers,
Torsten Fritzel and Carlo Rizzo for their help and useful comments on reviewing parts of
this book.

Thereza M. Macnamara
Series Preface

In many of the books in this Series to date, the functions of the aircraft systems, mission systems and avionics have been described for both commercial and military aircraft types. One thing was omitted in most descriptions of communications, navigation, identification and surveillance systems – the role of the antenna.

That omission has been corrected in this important reference book on the care and attention needed to select the right antenna and to define its location on the airframe. That airframe is a crowded piece of real estate where systems engineers compete for the best site for optimum performance of their system. Antennas must be placed to ensure system performance and satisfy aerodynamic considerations, whilst ensuring interoperability and preventing mutual interference.

This book shows how antennas designs are analysed, modelled and tested throughout the aircraft design process to ensure the optimum results for systems performance. This is a book for antenna, systems engineers and for specialist practitioners in radio frequency applications for both commercial and military aircraft.

Allan Seabridge
1

Basic Antenna and Propagation Theory

1.1 Introduction

This chapter explains the principles of antenna theory and propagation qualitatively, without going into the complex mathematical equations that are usually found in textbooks and reference books dealing with these subjects. Although this results in explanations of a simplistic nature, it enables the reader with a basic physics background to understand electromagnetic (EM) theory.

EM waves are transverse waves, unlike sound and ultrasonic waves, which are longitudinal waves that require a medium. By analogy transverse waves are like the waves one would obtain by moving a rope up and down to transmit a sine wave, whereas a longitudinal wave is like a series of train wagons being shunted along, so that each wagon moves horizontally back and forth whilst the wave also moves horizontally along the whole train.

Sonic waves cannot be transmitted in a vacuum, whereas EM waves do not require a medium and can be transmitted in a vacuum, such as deep space. This is why we can see the stars but do not hear the sound of meteors, and so on.

The EM spectrum extends from direct current (DC) that has no/zero frequency to cosmic radiation.

Above DC, we commonly encounter low frequencies from 3 Hz up to around 300 Hz used for communications with submarines.

Alternating current (AC) frequencies are used to transmit mains power. In Europe 50 Hz is used, whereas in North America and some other countries 60 Hz is more common.

The mains power on aircraft is usually 400 Hz. There are various reasons for the choice of this frequency for powering aircraft systems, one of them being that this frequency was selected as a compromise between weight, size and efficiency of the aircraft power units.

Above these frequencies, there are many applications such as communications with mines, broadcasting, and so on, until the frequency used in aircraft systems which extends into the microwave and millimetre wave region. The details of the aircraft systems are covered in Chapter 2.
We then have the higher frequencies used for radio astronomy before the infrared (IR) region where we have the heating effect. Then we move into the optical or visible region of the spectrum which is actually a very small range of frequencies.

Above these frequencies, we have the ultraviolet (UV) region which causes sunburn at its high frequency end. Much of the UV light is absorbed by the atmosphere, and thus the higher levels are only encountered in hills and mountains. It is worth noting that photochromic lenses darken on exposure to UV light and therefore do so much more quickly at higher altitudes, whereas they take a lot longer to darken in a car, where most of the UV is absorbed by glass. UV is not absorbed by plastics and thus can penetrate the Plexiglas of aircraft windows/portholes. EM waves up to these frequencies are non-ionizing.

Above ultraviolet the EM waves are ionizing and penetrate materials such as tissue, in the case of X-rays, and even concrete, in the case of gamma rays. Then we have cosmic rays that originate in space.

All these forms of radiation are in the EM spectrum; however, when engineers refer to Electromagnetics (in the case of antennas) or electromagnetic health (EMH) they usually are only referring to the EM spectrum from about 1 kHz to about 300 GHz.

The term antenna is used as a generic term for wire antennas such as dipoles as well as for aperture antennas such as horns, reflectors, and so on.

In some cases however, the term ‘antenna’ is restricted to aperture antennas in the upper radio frequencies (RFs) and microwave regions – above about 500 MHz – and the term aerial is used at the lower frequencies.

In guided circuits, such as wire and printed circuit tracks that have resistive and reactive components (inductors and capacitors), the electric and magnetic fields are 90° out of phase, but in free space the electric and magnetic fields are in phase.

1.2 Characteristics of Electromagnetic Waves

In order to understand the propagation of EM fields, all the properties of radiation have to be considered. The main phenomena that affect the propagation are reflection, refraction and diffraction.

At a macroscopic level we can think of EM radiation as travelling in straight lines, but at a microscopic level we have to consider the wave properties of the radiation as well.

If we think of the waves as spherically emanating from the source (like the waves obtained by throwing a pebble into the water), then the spherical shells are the wavefronts and the rays are the radii from the source and therefore perpendicular to the wavefronts. In Figure 1.1 the wavefronts and rays are shown in two dimensions for clarity.

Reflection and refraction can be explained by the rectilinear propagation (light travelling in straight lines) of EM waves, but diffraction can only be explained by the wave theory. Geometric optics deals with rectilinear propagation, whereas physical optics deals with light as waves. Figure 1.2 shows the rays produced in a plane normal to the cylinder axis, for an antenna located off the body of the cylinder. The stronger the colour, the greater is the intensity of the ray.

Figure 1.3 is a graphic indication of the rays reflected and diffracted off an airframe.
1.2.1 Reflection

Reflection is explained by Snell’s first law, which states that if an incident ray strikes a planar reflecting surface, it is reflected at the same angle to the normal as the incident angle and that the incident, normal and reflected rays are all in the same plane. Snell’s laws are named after the Dutch mathematician Willebrord Snellius (1580–1626).
The incident angle $i$ is the angle between the incident ray and the normal to the surface, and the reflected angle $r$ is the angle between the reflected ray and the normal to the surface, as shown in Figure 1.4a.

In the case of light waves, we can understand this phenomenon quite easily since we encounter it when looking in a plane mirror. However, if we consider a surface that only partially reflects the light, for instance parts of the dashboard reflected in the windscreen, then we are more likely to understand the EM waves reflected by surfaces that do not reflect most of the EM wave. In the case of the surface of an aircraft the complex reflected waves are akin to the images seen in the ‘crazy’ mirrors of a fairground.

In the case of a flat, perfectly conducting surface, the reflected ray would be similar to that obtained from a mirror, and in RF terminology this is called specular reflection.

If the surface is uneven, as in the case of most airframes, then there will be diffuse reflection, with waves scattered in a number of directions, in the same way as a sheet of white paper would diffuse the light falling on it.

When we say that a surface is flat or uneven, we mean relative to the wavelength of the radiation falling on it. For instance, if a surface roughness varies by 1 mm as shown in Figure 1.4b, this surface would be smooth/flat to a EM wave of 500 MHz that has a wavelength of 60 cm, whereas it is rough to visible light of frequency 450 THz (450 × 10^12) that has a wavelength of 0.7 μm.

This unevenness also explains diffuse reflection obtained, for instance, when light falls on a sheet of white paper. A parallel beam of light falling on an arbitrarily uneven surface is shown in Figure 1.4c, and we can see that the reflected rays are scattered in several directions, known as diffuse reflection.

Apart from the direct wave that is propagated into free space, the first order reflected wave (i.e. the first reflected wave that is the result of a direct wave striking a reflecting surface) contributes the greatest to the resultant in the far field. If the first order reflected wave is in phase with the direct wave, then the resultant would a maximum, whereas if the first order reflected wave is in antiphase (180° out of phase) with the direct wave then the resultant would a minimum.

1.2.2 Refraction

In real life we encounter the phenomenon of refraction when looking into a swimming pool where the floor of the pool appears less deep than it actually is. Refraction is the bending of rays when an incident ray strikes a medium with a different refractive index. In
general, the denser media have higher refractive indices. Spectacle lenses that are thinner usually have higher refractive indices, to attain the same power (dioptre).

Refraction is explained by Snell’s second law, which states that when an incident ray enters a more optically dense medium (i.e. with a higher refractive index), it is bent towards the incident ray. Conversely, if it enters a less dense medium, it is bent away from the incident ray, as shown in Figure 1.5.

Snell’s law is expressed as

$$\mu_1 \sin i = \mu_2 \sin r,$$  \hspace{1cm} (1.1)

where

- $\mu_1$ is the refractive index of the first medium
- $i$ is the angle of incidence at the interface between the first and second medium
- $\mu_2$ is the refractive index of the second medium
- $r$ is the angle of refraction.

For instance, if the first medium has a refractive index of 1 (like air), the second medium has a refractive index of 1.4 and the angle of incidence is $36^\circ$, using Equation 1.1 the refracted angle is $24.8^\circ$.

However, if the refractive indices were reversed and the wave was travelling from a medium with a refractive index of 1.4 to one with a refractive index of 1, then the refracted angle would be $55.4^\circ$, as shown in Table 1.1.

If the second medium is in the form of a plate where the top and lower surfaces are parallel, then the ray emerging from the plate will be parallel to the incident ray but displaced from it by a distance that is directly proportional to the thickness of the plate.

![Figure 1.5](image.png)  

**Figure 1.5** Snell’s law of refraction.

<table>
<thead>
<tr>
<th>$\mu_1$</th>
<th>$\mu_2$</th>
<th>Angle $i$</th>
<th>Angle $r$</th>
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<tbody>
<tr>
<td>1</td>
<td>1.4</td>
<td>36</td>
<td>24.8</td>
</tr>
<tr>
<td>1.4</td>
<td>1</td>
<td>36</td>
<td>55.4</td>
</tr>
</tbody>
</table>
In the case of aircraft antennas the materials that would subject the EM waves to refraction are composite fibreglass dielectric surfaces like those used in radar domes (radomes) that protect the antennas whilst still allowing the radiation to pass through them.

In Figure 1.6 we can see that as the thickness of the plate is increased the displacement of the emerging ray is also increased. The thickness that we have to consider is the electrical thickness, that is, the thickness in terms of wavelength. Thus if we keep the physical thickness the same but double the frequency the wavelength will have halved, and so that is tantamount to doubling the thickness of the plate. The displacement will be double the amount for the higher frequency (assuming that the refractive index has also doubled with frequency). This accounts for the fact that the fibreglass covering used for low frequency antennas such as ‘blades’ can be quite thick, but in the case of the nose cones the radomes have to be thin. If the radomes have to be strong enough to withstand birdstrike, for instance, then the radomes are made of several layers, where the effect of some of the layers compensates for the adverse effect of other layers. These are known as sandwich radomes.

We must also consider the effect of increasing the refractive index. If the refractive index is increased, the refracted ray is bent more and thus the emerging ray is more displaced compared to the incident ray. This can be seen in Figure 1.7. When the refractive index \( \mu_2 \) of the plate is increased to a larger value \( \mu_3 \) the emerging ray is displaced to a larger extent.

It should also be noted that the refractive index of the same material varies with frequency, and in general it increases with increasing frequency.

### 1.2.2.1 Total Internal Reflection

We have seen how a ray entering a medium of lower refractive index is bent away from the normal according to Snell’s law. At a certain angle of incidence \( i_c \) known as the critical angle, the angle of refraction is \( 90^\circ \) so that the ray travels along the interface between the two media, as shown in Figure 1.8.

At angles of incidence greater than \( i_c \), the ray is refracted back into the first medium. Because the ray now behaves like a reflected ray, with the angle of reflection equal to the angle of incidence, this effect is known as total internal reflection.