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Large-area optical scattering setup for high- performance optical surfaces

Beatriz da Fonseca Lopes

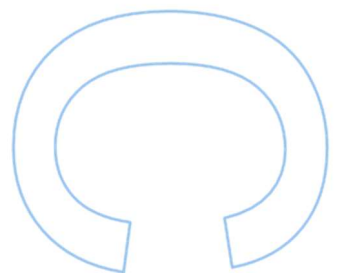
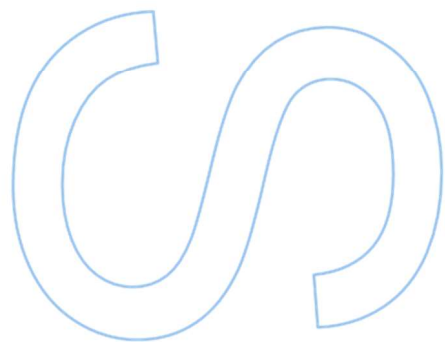
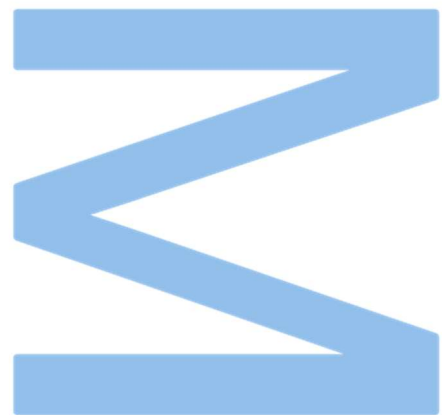
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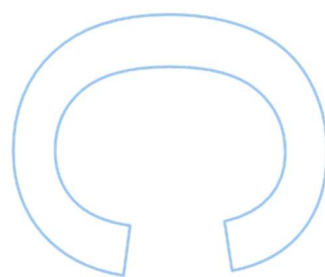
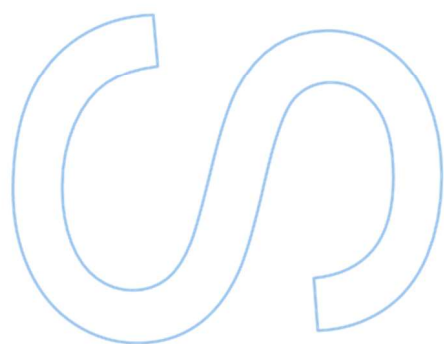
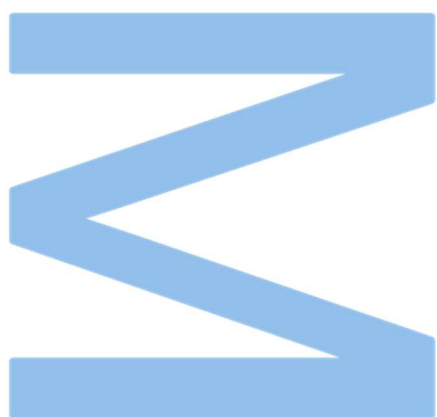
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*" If I can't understand it, I'll find another way
Keep moving, keep moving "*

Keep Moving in *Loving in stereo*, written by Jungle

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UNIVERSIDADE DO PORTO

Abstract

Faculdade de Ciências da Universidade do Porto

Departamento de Física e Astronomia

MSc. Engineering Physics

Large-area optical scattering setup for high-performance optical surfaces

by [Beatriz LOPES](#)

In this work, an experimental system was developed to measure optical scattering on flat surfaces, essential for advanced optical systems, specially for complex ones such as Lidar. The project began with a thorough analysis of Bosch's scattering measurement system, identifying key areas for improvement. Key elements such as pinhole and iris diaphragm apertures, lens focal length, and laser beam size were evaluated, leading to a new design that offers smoother measurements with an expanded dynamic range. The resulting system facilitates scanning large sample areas with high angular resolution, enabling detailed analysis.

The system design and model were developed and evaluated using an optical simulation tool. This tool allowed evaluating and establish the relationships between the experimental setup degrees of freedom. The implementation, calibration, and testing phases followed, culminating in a system that characterizes optical scattering with greater precision and less noise, suitable for large samples. This innovative system optimizes the functionality and reliability of critical optical components like mirrors, transmission windows, filters, and optomechanical parts.

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Resumo

Faculdade de Ciências da Universidade do Porto

Departamento de Física e Astronomia

Mestrado Integrado em Engenharia Física

Configuração experimental de espalhamento ótico de grande área para superfícies óticas de alto desempenho

por [Beatriz LOPES](#)

Com este trabalho desenvolveu-se um sistema experimental para medir a dispersão ótica em superfícies planas, essencial para sistemas óticos avançados, especialmente os complexos, como o Lidar. O trabalho iniciou-se com uma análise detalhada do sistema de medição de dispersão da Bosch, identificando áreas-chave para melhoria. Elementos essenciais, tais como aberturas de diafragma de pinhole e íris, comprimento focal da lente e tamanho do feixe laser, foram avaliados, conduzindo a um novo design que oferece medições mais suaves e com um alcance dinâmico expandido. O sistema resultante facilita a varredura de grandes áreas de amostra com uma resolução angular adequada, permitindo uma análise minuciosa da amostra sob estudo.

O design e o modelo do sistema foram desenvolvidos e avaliados utilizando uma ferramenta de simulação ótica. Esta ferramenta permitiu avaliar e estabelecer as relações entre os graus de liberdade do conjunto experimental. Seguiram-se as fases de implementação, calibração e testes, culminando num sistema que caracteriza a dispersão ótica com maior precisão e menos ruído, adequado para diferentes tipos de amostras. Este sistema otimiza a funcionalidade e a fiabilidade de componentes óticos críticos, como espelhos, janelas de transmissão, filtros e partes optomecânicas.

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Symbols

$\mathbf{E}$	Electric field vector
$\mathbf{B}$	Magnetic field vector
ρ	Charge density
ϵ_0	Vacuum permittivity
μ_0	Vacuum permeability
$\mathbf{J}$	Current density
t	Time
I_s	Scattered light intensity
I_0	Incident light intensity
θ	Scattering angle
λ	Wavelength of light
r	Particle radius
R	Distance from the scatterer to the observer
n	Index of the medium
a_n, b_n	Mie coefficients
$\psi_n(m, x)$	Mie angular function
$\xi_n(m, x)$	Mie radial function
m	Relative refractive index
x	Size parameter
$f(\mathbf{k}, \mathbf{k}')$	Scattering amplitude
m	Mass of the particle

$\hbar$	Reduced Planck's constant
V	Scattering potential
$\mathbf{k}, \mathbf{k}'$	Initial and final wave vectors
$r_{\text{parallel}}, r_{\text{perpendicular}}$	Reflection coefficients for parallel and perpendicular polarization
$t_{\text{parallel}}, t_{\text{perpendicular}}$	Transmission coefficients for parallel and perpendicular polarization
n_1, n_2	Refractive indices of the two media
θ_i, θ_t	Incident and transmitted angles

Glossary

AD	Autonomous Driving
ADS	Automated Driving Systems
ADAS	Advanced Driver Assistance Systems
SAE	Society of Automotive Engineers
LiDAR	Light Detection and Ranging
RADAR	Radio Detection and Ranging
FoV	Field of View
EM	Electromagnetic
BSDF	Bidirectional Scattering Distribution
BRDF	Bidirectional Refletance Scattering Distribution
BTDF	Bidirectional Transmittance Scattering Distribution
DSF	Differential Scattering Function
MFD	Mode Field Diameter
EO	Eletro-optical
NSDD	Non-sequential incoherent intensity data
NSTR	Non-sequential ray trace

*This work is dedicated to my father Manuel and my nephew
Manuel.*

Chapter 1

Introduction

1.1 Context

Autonomous driving (AD), which a few years ago appeared to be a distant concept limited to scenes of science fiction, autonomous cars not only arrived but also developed rapidly, powered by the substantial investment from companies in the automotive industry. This technology is transforming the role of the vehicle and of the driver. [1]

According to a study conducted by the European Commission's Directorate-General for Mobility and Transport, about 95% of road accidents involve some level of human error. It's estimated that 75% are caused only by human error. The primary human factors identified in relation to these accidents are excessive speed, distraction, and driving under the influence of alcohol. [2]

The majority of road accidents are attributed to human error, therefore the effort to develop more sophisticated automated driving systems (ADS) has been the goal for improving road safety. In a study conducted by the international automotive distribution, researchers showed that the adoption of advanced driver-assistance systems (ADAS) like automated emergency braking, blind spot monitoring, and lane assist in Europe could reduce the number of accidents by about 15% by 2030 [3]. Such technology not only has the potential to improve transportation system efficiency, reduce emissions of greenhouse gases and air pollutants, but also decrease driving-related stress and elevate the comfort of both the driver and passengers. ADS vehicles can also play a crucial role in promoting social inclusion. For the elderly and individuals with reduced mobility or disabilities, these vehicles offer a chance to access new opportunities and improve their quality of life. [1]

Owing to the numerous advantages this technology can provide, companies such as Bosch, Continental, Delphi Automotive, Freescale, Texas Instruments, and many others have entered the market and are offering diverse types of ADAS solutions for End-User Applications. According to McKinsey analysis, AD could generate between \$300 billion and \$400 billion in the passenger car market by 2035. [4] A wide range of automated systems are already on the market, either in private vehicles (cars and trucks) and public vehicles (buses). The high demand has led to a large investment in increasingly sophisticated ADS technologies such as LiDARs (Light Detection and Ranging), imaging RADARs (Radio Detection and Ranging) and others. Despite being in a very immature phase of development, these new technologies have the potential to revolutionise the automotive industry.

To standardise and categorise the diverse automated technologies across both technical and policy fields for all companies, the Society of Automotive Engineers (SAE) [5] introduced a classification system for road vehicles. This classification defines six levels, from Level 0, signifying no automation, to Level 6, denoting full automation. [6] The SAE International's levels of automation are shown in figure 1.1. From level 0 to 2, human drivers monitor the environment, whereas in levels 3 to 5, certain systems can monitor and react to the surroundings without human intervention.

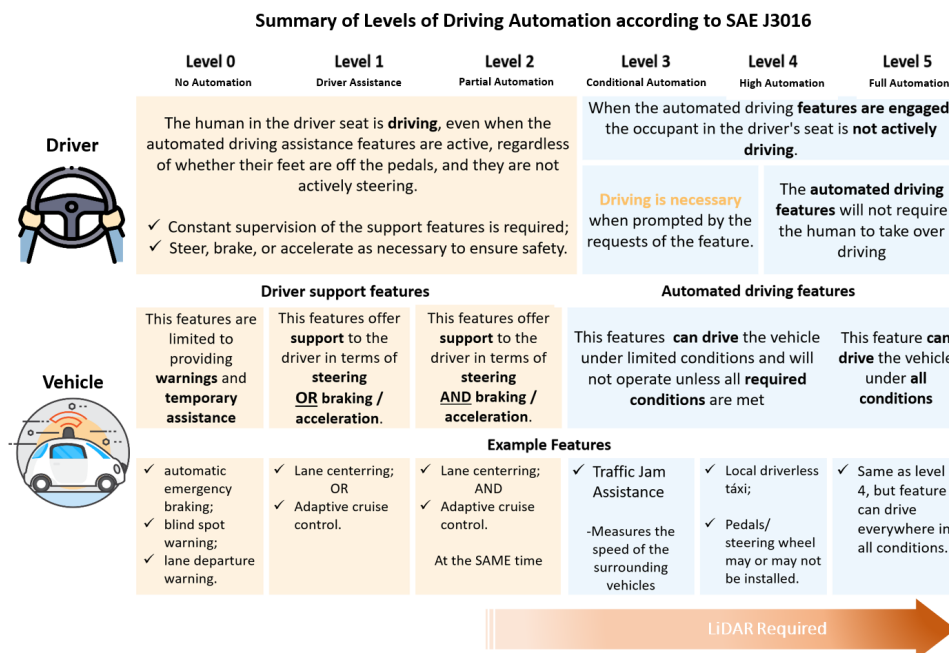


FIGURE 1.1: SAE Levels of Driving Automation™. Source: [5]

Automated Driving Systems, as human drivers, must constantly monitor and react to their environment. To do so, vehicles use a variety of integrated sensors to perceive their surroundings, including cameras, radar, LiDAR, and ultrasonic sensors. All sensing, planning, and action need to be executed in mere fractions of a second, creating a continuous feedback loop to ensure a seamless and safe driving experience [1]. No single sensor can consistently provide accurate detection, classification, measurement, and resilience in challenging conditions. Different sensors also feature distinct characteristics, with varying sensitivities to adverse weather and illumination conditions. Among these sensors, cameras play a crucial role in ADS due to their unparalleled ability to extract detailed visual information, closely simulating human perception. These devices are adapted to provide sharp angular resolution and stand out in recognizing and classifying objects. Simultaneously have a commendable range, field of view (FoV), and can handle different lighting conditions. Yet, despite possessing these capabilities, challenges such as the determination of distance and velocity of a moving vehicle, and the performance can also be compromised under adverse weather conditions, due to the high sensitivity to external factors. [1, 7]

LiDAR steps in to fill some of these gaps. LiDAR is known for its precise distance measurement and high-precision assessment of both different types of elements. It also presents high performance even at low illumination, because it has an external light source. Furthermore, LiDAR can achieve a wide FoV range. However, several limitations are exhibited by LiDAR. It is characterized by medium sensitivity to environmental conditions, and its performance in terms of velocity resolution, angular resolution, object classification/semantic information, and complete coverage of object surfaces is found to be moderate. Another substantial drawback of LiDAR is the complexity of the perception algorithms that need to be able to make sense of the data collected. Additionally, Radar sensors are used for vehicle and large objects detection. These sensors offer high-precision detection and measurement of moving objects with appropriate reflectivity within their operational range, boasting strong performance during nighttime and robustness against diverse weather conditions. However, their capabilities in angular resolution and understanding or interpreting objects are only moderate. They also provide average results of FoV and object classification, while their detection range, velocity resolution, and reliability under varied lighting conditions stand out as their primary strengths. Ultrasonic sensors are equipped with a well-established near-field sensor, capable of detecting the

closest distances to reflecting entities and exhibiting good performance in low light environments. [1, 7]

The quality and the reliability of the Advanced driver-assistance system (ADAS) is achieved by combining all the sensors mentioned above and even some more. This approach leverages the strengths of one sensor to offset the limitations of another, ensuring enhanced functionality even in challenging conditions, like adverse weather conditions. Figure 1.2 shows a 360° schematic of the sensors in an ADAS-equipped vehicle.[1, 7]

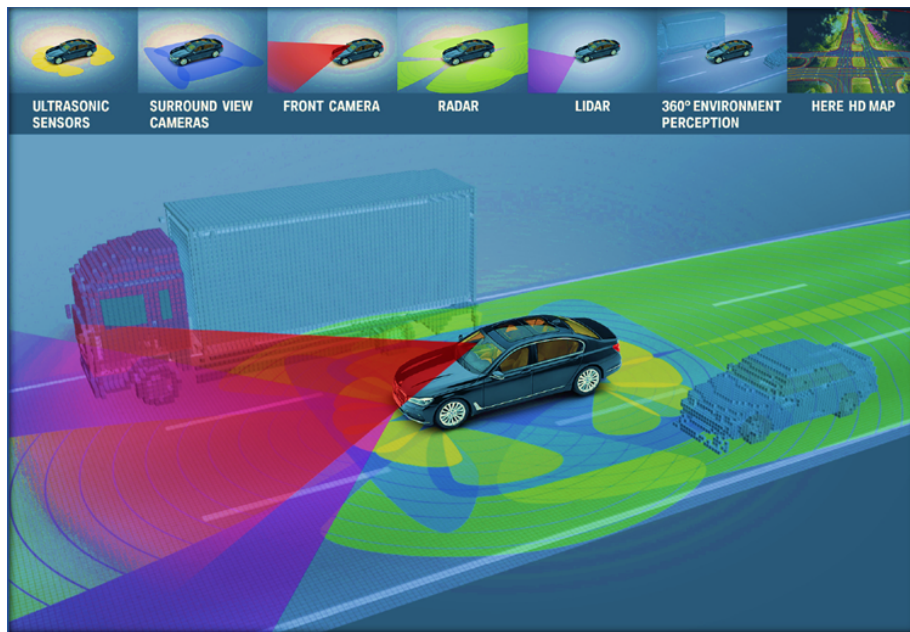


FIGURE 1.2: ADAS sensor's – combination of multiple sensors to ensure a complete perception of the surroundings. Source: BMW [1]

ADAS is changing mobility, an intrinsic part of our lives and experiences. With advancements in autonomous driving, electrification, and increased connectivity, we are on the point of discovering new ways to travel. These innovations extend beyond reshaping car journeys, they hold the potential to transform our lifestyle and the way we live in society.

1.2 LiDAR's technology in Automated Driving Systems

1.2.1 Brief history of LiDAR sensors

Multiple methods have been developed for detection and ranging of objects, including sound detection and ranging (SONAR), radio wave detection and ranging (RADAR), and light detection and ranging (LiDAR). [8]

LiDAR is a remote sensing method that uses a pulsed laser to measure distances from the laser emitter to a target [9]. Developed shortly after the invention of the laser in the 1960s, LiDAR technology initially found applications in meteorological data acquisition and lunar topographical mapping as part of the Apollo space missions. In the late 1980s and throughout the 1990s, the technology found new applications in aerial topographical mapping and forest canopy analysis. Fast-forward to the early 21st century, and LiDAR's utility expanded into geological investigations, most notably subsurface characterization, as well as vehicular automation systems. This expansion was exemplified by its implementation in the 2005 DARPA Grand Challenge, a competition for self-driving cars. This led to increased interest from automotive companies in investing in this technology to achieve higher levels of autonomous driving. In recent years, the technology has become more compact and affordable, which lead to diverse applications in drone mapping, environmental monitoring, and consumer electronics like smartphones and drones. Advances in solid-state LiDAR are promising to further reduce costs and expand applications, signalling a vibrant future for the technology. As LiDAR continues to evolve, its range of applications keeps increasing, benefiting from ongoing advancements in resolution, portability, and affordability.

1.2.2 LiDAR: basic operation principles

LiDAR, operates by emitting electromagnetic (EM) waves in both the optical and infrared spectral regions, and then capturing the backscattered light. Unlike passive electro-optical (EO) sensors that rely on ambient radiation, LiDAR is an active sensing system, which means that it generates and emits its own radiation, rather than relying on external sources [9].

One of the measurement principle of LiDAR is time-of-flight (TOF) (see Fig.1.3). In this approach, the depth of a target is determined by measuring the time delay between emitting a pulse of light and receiving the backscattered signal from the target. The time-of-flight (t_{oF}) is the duration it takes for the pulse of light to travel from the emitter to the target object and back to the receiver. This time is used to calculate the distance (R) to the target, based on the round-trip delay of the emitted EM wave.[10] Mathematically, this can be represented by the equation 1.1. [10]

$$R = \frac{c}{2}t_{oF} \quad (1.1)$$

Where ($c = 3 \times 10^8 \text{m/s}$) is the speed of light in free space.

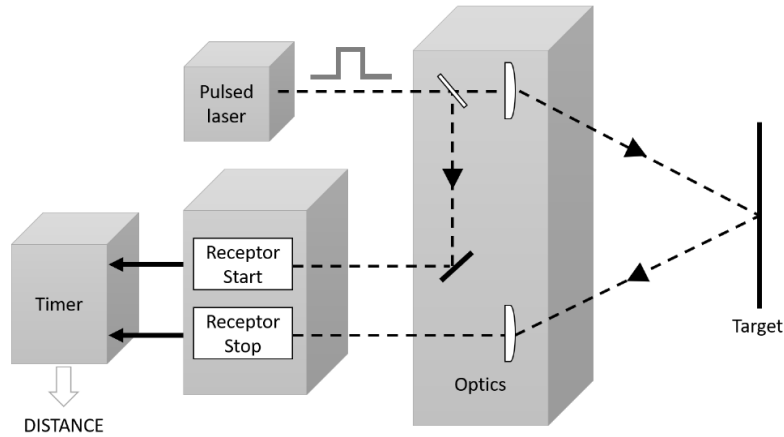


FIGURE 1.3: Pulsed time-of-flight (TOF) measurement principle. Source: [10]

By employing TOF measurements, LiDAR systems can generate a three-dimensional point cloud representation of the sensor's proximal environment, enabling highly accurate spatial mapping. This technology has advantages in terms of angular resolution since it operates with short wavelengths, and it is capable to operate uninterruptedly, even in scenarios with low illumination.

Unlike simple 2D imaging systems, LiDAR can produce 3D images by measuring the range to each pixel. Additionally, LiDAR can capture traditional greyscale images and determine the colour of objects by using multiple wavelengths. It can even measure object velocity through techniques like the Doppler shift. In coherent LiDAR systems, the Doppler shift is utilized to measure the velocity and micro-motions of objects. This is achieved through the Doppler effect, which detects changes in the frequency of the returned light signal. However, these systems encounter challenges stemming from a phenomenon known as "speckle." Speckle arises from the constructive and destructive interference of narrowband light waves, making image interpretation more complex. Although speckle changes the imaging process, it can also be leveraged to gain additional insights into the surface characteristics of the object being observed. This is because the pattern of speckle can reveal information about the surface's texture and other features. These different characteristics make LiDAR a very versatile sensor.

The operating wavelength and frequency are also significant in determining the potentials and limitations of LiDAR, as higher frequencies are commonly employed by LiDAR

systems to achieve high-resolution imaging. Unlike traditional radar systems, which operate at lower frequencies, more detailed information can be provided by LiDAR. However, the effectiveness of LiDAR is reduced when interacting with obstacles like fog or rain due to the utilization of such high frequencies. The performance of LiDAR can be affected by weather conditions, as fog particles and rain droplets own dimensions that are similar to or larger than the wavelengths emitted by LiDAR, causing the signals to be scattered or attenuated. This effect will be detailed further in Chapter 2. Most commonly, the wavelengths used in Lidars are 905 nm and 1550 nm. Each wavelength serves distinct objectives and possesses unique advantages and drawbacks. Although safety is a primary concern that often leads to the preference for 1550 nm in high-power LiDAR systems due to its eye-safe characteristics. Systems with 905 nm can also be made eye-safe if designed in compliance with regulatory standards such as the U.S. FDA and IEC 60825. 905 nm is often utilized in lower-power applications, where it can meet the highest safety classifications when suitably designed.[10, 11] Another essential factor is atmospheric absorption, where different wavelengths have varying susceptibilities. While wavelengths for LiDAR are generally selected to have minimal absorption, guaranteeing longer-range and more trustworthy operation, 905 nm demonstrates superior performance in adverse weather conditions. Unlike 1550 nm, which experiences significant signal degradation in rain, fog, and snow, 905 nm is more weather-resistant and is thus recommended for applications where all types of environmental conditions must be taken into account. [11]

Within the evolving landscape of the automotive industry and with a shift towards electric vehicles, consideration of energy power consumption gets more importance. Because of that, lowering the vehicles consumptions is mandatory. LiDAR systems operating at 1550 nm are exceptionally energy-intensive, generally necessitating up to ten times the power required by systems at 905 nm. This increased demand for energy leads to the need for systems that are more complex and sizeable, incorporating additional components for power and cooling, consequently diminishing the attractiveness of 1550 nm wavelengths for electric vehicles. [11] The selection of wavelength also has economic implications. The 905 nm wavelength matches well with silicon photodetectors, making it generally more cost-effective. In contrast, the use of more expensive InGaAs detectors is often necessitated by 1550 nm, and custom-made components can be required, contributing to increases in both cost and supply chain complexity. [11] Commercial accessibility is recognised another crucial factor, cost advantages and higher availability can

be offered by wavelengths that are commonly used in other industries. The selection of wavelength may be influenced by considerations of compatibility and sensor fusion, particularly when LiDAR is incorporated as a component within multi-sensor compositions in Advanced Driver-Assistance Systems (ADAS). [10, 11]

1.2.3 Applications, including Bosch's long-range sensor

LiDAR has wide-ranging applications in both civilian and military sectors. It can be used to characterize objects based on geometry, surface character, surface noise, and effluents. These properties make LiDAR a powerful tool for object identification, well-suited to tasks that require detailed, multidimensional information about a scene or object. One of the inherent advantages of LiDAR over traditional RADAR is its similarity to the optical systems human eyes are used to. While interpretation of RADAR images is often complicated due to their reflectance characteristics, images provided by LiDAR are similarly to those perceived by the human eye, making object recognition more intuitive (see Figure 1.4). This feature is found especially valuable in applications where fast and accurate identification of objects is crucial, such as in the navigation of autonomous vehicles.

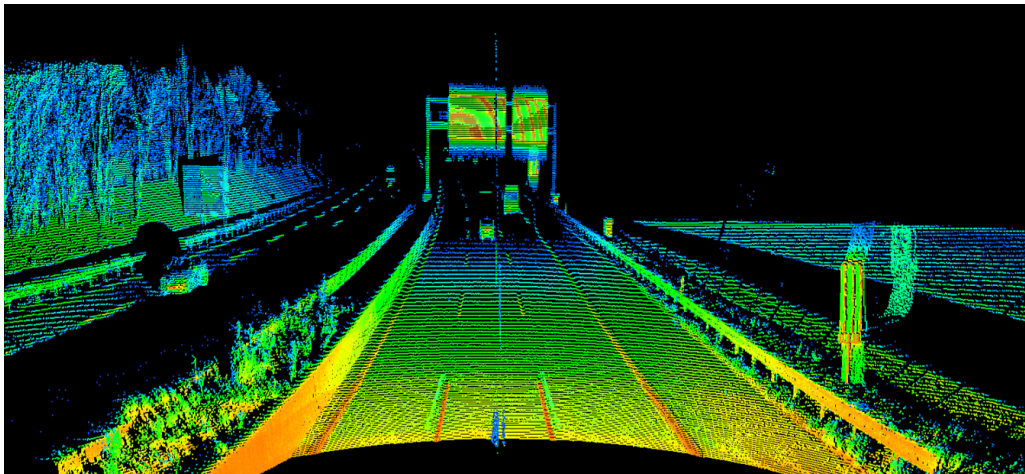


FIGURE 1.4: Bosch's LiDAR point cloud. Source: Bosch

Bosch long-range LiDAR sensor (see Figure 1.5) is designed to resolve complex and critical use cases, such as the detection of free space. Small objects at extended distances can be detected by it, enabling comfortable braking and safe automated driving. Small and fast-moving objects, such as motorcycles in crossroad scenarios, are also detectable by this sensor. When two objects are encountered in proximity, for instance, a pedestrian

next to a guard rail, they can be distinguished by this sensor. A detection range exceeding 200m is featured by this sensor, with power consumption maintained below 20W.

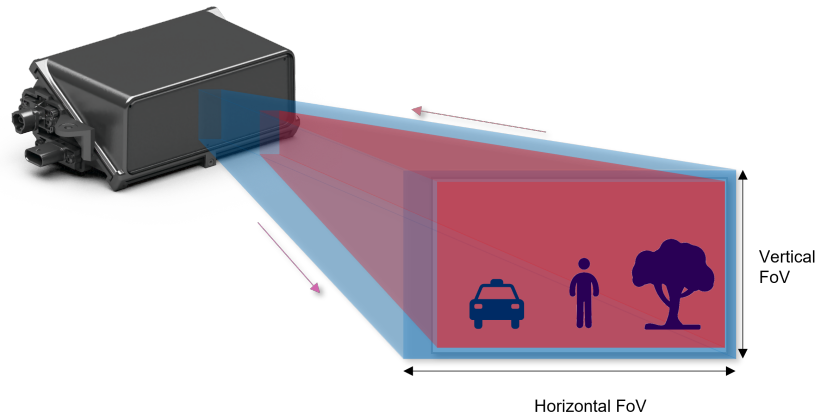


FIGURE 1.5: Bosch Long-range LiDAR. Source: Bosch

1.3 Internship objectives

This work was carried out during my internship at the Bosch Research and Development Center in Braga, focused on improving the quality of optical sensors, crucial for autonomous driving. Acknowledging that imperfections in these sensors can lead to significant malfunctions and accidents, the primary purpose was to develop a system capable of accurately measuring optical scattering in a larger area on flat surfaces. The project began with the design and modelling of this system using an advanced optical simulation tool. This tool was instrumental in understanding the interaction between various optical parameters and their impact on sensor performance. The objectives extended to the practical implementation and calibration of the system in Bosch's laboratories, followed by precise measurements and analysis of optical samples. Through these steps, the project aimed to contribute to the characterization of optical scattering, thereby ensuring higher quality and reliability in the sample scattering measurements. The outcome of this work is to have a more effective system to measure the scattering, using a larger area scattering setup, with smoother and wider results that could give us more accurate information about the samples being measured.

1.4 Report structure

- **Chapter 1** delineates the motivating factors for this internship, offering a review of the evolution of Advanced Driver-Assistance Systems (ADAS) and the role of LiDAR technology therein, with a focus on its applications in autonomous vehicles. This chapter also introduces the motivation and objectives of the project.
- **Chapter 2** presents the physical concept of light scattering, explaining its origins and its dependence on the size of particles. A brief introduction is provided, supported by illustrative examples, and various forms of scattering are explored. The relationship between scattering and stray light is also examined.
- **Chapter 3** provides a detailed overview of ASTM standard E2387-19, highlighting the scattering setups used and the main considerations and precautions during implementation. The Bidirectional Scattering Distribution Function is theoretically described. This chapter also outlines conventional scattering systems utilized in the experiments, showing and characterising the experimental elements.
- **Chapter 4** outlines the specific parameters and configurations studied to understand their influence on the performance of our optical measurement system. It digs into aspects such as laser beam size, distances between elements, lens focal length, pin-hole aperture size. Additionally, provides a comparative analysis of two distinct system designs: the existing setup and the new large area configuration currently in development. By emphasizing the unique characteristics and structural differences between these setups, it lays the foundation for comprehending the improvements offered by the new large area configuration. Providing a technical examination of these parameters and their implications for precise optical measurements, establishing the critical role of system design in achieving accuracy.
- **Chapter 5** specifies the experimental methods employed for the calibration and implementation of the setups, and characterises the samples and lens used in the large area setup. This chapter also presents the results and engages in a detailed discussion of the measurements results of both setups.
- **Chapter 6** Final conclusions are drawn, and a comparative analysis between the two setups is provided. The future work is presented in the end.

Chapter 2

Fundamental aspects of scattering

This chapter aims to provide an overview of the fundamental aspects of light scattering, an essential optical phenomenon. Initially, the foundational principles that postulate this phenomenon will be explained. This is followed by a brief explanation of the various types of scattering are elaborated upon, and the importance of measuring scattering in diverse applications is emphasized. In addition, there will be a brief introduction to stray light, its causes and the consequences this phenomenon has on optical systems. The chapter concludes by drawing a correlation between these two optical phenomena. It should be noted that, although not all stray light originates from scattering, scattering is identified as a significant source of stray light in many optical systems.

2.1 Scattering effects

The majority of materials scatter light in various directions, a phenomenon known as diffuse scattering. Only a few materials, like perfect mirrors, reflect light in a single direction, known as specular reflection. If all materials behaved like mirrors, visual perception would be far more complex. [12] While all scattered light plays a role in shaping our perception, certain phenomena are particularly important. Rainbows occur due to the dispersion and reflection of sunlight in water droplets. Alpine glow (often called Alpenglow - Figure 2.1) arises from the scattering of sunlight by atmospheric particles, especially detectable at low sun angles. Sunsets feature the effects of Rayleigh scattering in the atmosphere, colouring the sky with hues of red and orange. These natural occurrences are a reminder that everyday we observe many light scattering phenomena.



FIGURE 2.1: Light scatter phenomena - 'Alpenglow' in Chugach Mountains. Source: [13]

The interaction of light, or electromagnetic (EM) radiation, with matter involves the interaction between charged particles, such as electrons and protons, and EM fields. The interaction between an EM field and matter forms dipoles. These dipoles absorb energy and emit electromagnetic fields. This complex process becomes even more complicated in liquids and solids due to the free behaviour of neighbouring dipoles.[12] Furthermore, if the object size that interacts is significantly larger compared to the wavelength, the amplitude, and phase of the excitation field can change, adding another layer of complexity to the system.

Maxwell's equations (Eq. A.1) are the foundational basis in electromagnetism, describing the spatio-temporal evolution of electric and magnetic fields. These equations are not only critical to understand static fields, but also to predict electromagnetic wave propagation. When simplified, they yield the wave equation (Eq. A.2), which is used to study light's dispersion through different surfaces and lays the basis for searching optical phenomena such as scattering.[14] When considering more complex systems like atoms and molecules, quantum mechanics takes the helm. Here, the Born approximation (Eq. A.3) offers invaluable insights into how electromagnetic waves interact with these intricate systems, extending the knowledge base of scattering theory into material science and solid-state physics. Furthermore, while not strictly considered scattering, the Fresnel equations (Eq. A.4) define how light behaves at the interface between two different media, explaining the closely related phenomena of reflection and refraction. These equations are crucial for a complete understanding of light's behaviour, especially since reflection and refraction often accompany scattering events.

Scattering can be classified into two main types: elastic and inelastic, as an effect of

the light interacting with particles or its direction changing due to entering an inhomogeneous medium.[15] In elastic, or coherent, scattering—such as Mie and Rayleigh scattering—there is no energy loss to the medium. Consequently, the wavelength of the scattered light remains identical to that of the incident light, although the direction of the wave vector may change [15, 16]. Inelastic scattering, on the other hand, involves the transfer of energy between the light wave and the scattering medium; Raman and Brillouin scattering are examples of this type of scattering. The change in energy of scattered light, which leads to shifts in frequency or wavenumber and changes in direction as seen in processes like Raman and Brillouin scattering, has three significant consequences: It enables precise material characterization, facilitates accurate temperature and pressure measurements, and aids in developing non-invasive medical diagnostics. [16].

2.2 Scattering behaviour

2.2.1 Rayleigh scattering

In 1871, British physicist Lord Rayleigh (John William Strutt) published a paper in which he mathematically described the scattering of electromagnetic radiation (often visible light) is scattered by particles that are much smaller than the wavelength of the incident light. Rayleigh scattering can occur in various mediums including gases, liquids, and transparent solids. However, it is most commonly associated with gases, like Earth's atmosphere, because gases are more likely to contain the small particles that are much smaller than the wavelength of visible light. In solids and liquids, the particles are often larger or the medium itself may not be perfectly homogeneous, leading to other types of scattering or absorption. [15] The Rayleigh scattering equation, see Equation 2.1, shows that the scattering of light is inversely proportional to the fourth power of the wavelength (λ^{-4}).

$$I_s = I_0 \left(\frac{8\pi^4 a^6}{\lambda^4 R^2} \right) \left| \frac{n^2 - 1}{n^2 + 2} \right|^2 (1 + \cos^2 \theta) \quad (2.1)$$

This relationship demonstrates that shorter light wavelengths are more efficiently scattered than longer ones because they have a higher dispersed intensity. [14, 15] This type of scattering increases with frequency. Therefore, smaller wavelengths (with blue color

in the light spectrum) are scattered more strongly than longer wavelengths (that corresponds to the red in the visible spectrum). When light from the sun interacts with the particles present in the atmosphere, the scattering of blue light is higher than the scattering of the rest of the visible spectrum, and this is partly why the sky appears blue. However, violet light is largely absorbed by the upper atmosphere, which is why we primarily see a blue sky rather than a violet one. At sunset, sunlight has to travel through a greater distance in through a dense atmosphere, causing the shorter-wavelength, blue light, to scatter further. This allows the longer-wavelength yellow, orange and red light to be more predominate in the sky.

Rayleigh scattering is used in various fields, such as meteorology (used in weather radar technology to interpret and forecast atmospheric conditions), optical communication (essential for optimizing the transmission of optical signals through optical fibers), astronomy (Rayleigh scattering in the atmospheres of planets and stars can give astronomers clues about the composition and properties of these elements) and so many others.

2.2.2 Mie Scattering

In the early 20th century, German physicist Gustav Mie extended Lord Rayleigh's original work on light scattering to describe the behaviour of light interacting with spherical particles of arbitrary size and refractive index.[17] This led to the formulation of Mie theory, initially published in 1908, which serves as a cornerstone in the field of scattering theory. Results from solving the Maxwell's equations for spherical particles with size comparable to or larger than the wavelength of the incident light. These solutions are often expressed in terms of infinite series involving Bessel functions and Legendre polynomials, which enable the calculation of the scattering and absorption of electromagnetic waves by the particle (see Eq. 2.2).

$$I_s = I_0 \left(\frac{2\pi}{\lambda} \right)^2 \left| \sum_{n=1}^{\infty} a_n \psi_n(m, x) + b_n \xi_n(m, x) \right|^2 \quad (2.2)$$

Though exact solutions for Mie scattering exist for spherical particles, the application to irregularly shaped or non-spherical particles is less straightforward and remains an area of research. Numerical methods like the Discrete Dipole Approximation (DDA) [18] or Finite-Difference Time-Domain (FDTD) [19] methods are often used for these cases.[15]

For larger scattering matter with complex shapes, it's often more practical to describe them using macroscopic properties like reflectivity, transmissivity, and the index of refraction. These properties are not intrinsic attributes of the material in isolation; instead, they are the collective result of many microscopic scattering and absorption events. Mie theory finds diverse applications across various fields, so it is important in understanding the scattering of light by different particles, such as atmospheric aerosols and water droplets in clouds. Specifically, the theory helps to explain why some clouds appear white or grey, a phenomenon primarily attributed to the presence of larger water droplets. Mie theory is also important in the study of light scattered by biological cells, climate science (fog, dust), medical diagnosis and remote sensing, among other applications. The variations in angular distribution patterns between Rayleigh and Mie scattering, which are fundamentally influenced by the size of the scattering particles relative to the wavelength of incident light, are illustrated in Figure 2.2.

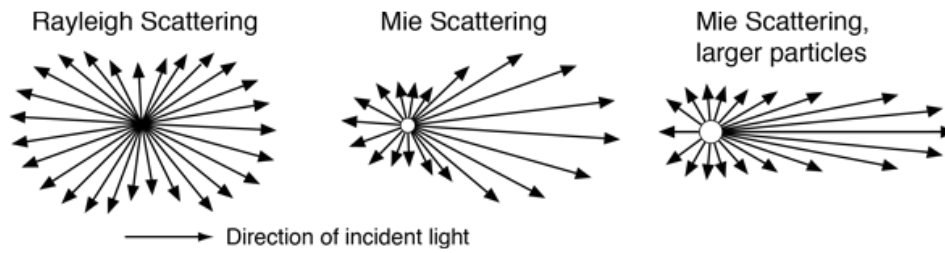


FIGURE 2.2: Rays distribution in Rayleigh and Mie scattering. Source: [8]

2.3 Study of Stray Light

Stray light is any EM radiation that is undesirable and interferes with the performance of an optical system's designate functions. [20] Understanding the light scattering properties of an optical system has become increasingly important in its design. This is because stray light is often primarily caused by the scattering from non-ideal behaviours of the optical components in the system, such as mirrors, slits, and gratings. [20, 21] Stray light can appear through partial reflection between the lens interfaces (ghosts) (Fig.2.3), or from scattering on the housing or due to the roughness of optical elements.[20]

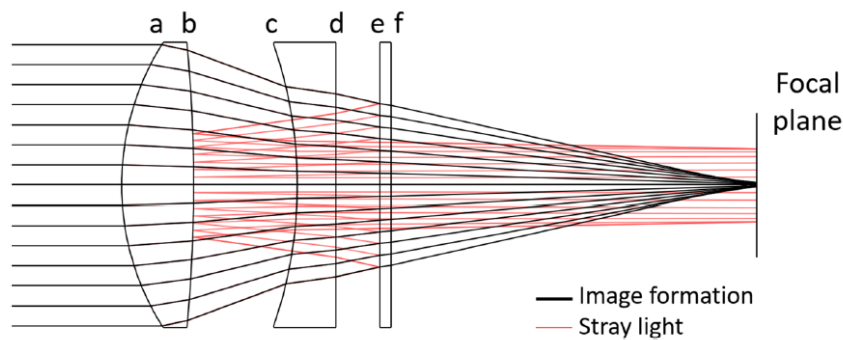


FIGURE 2.3: Sketch of the optical system, composed of two lenses and an optical window. Optical paths such as ghost reflections between surfaces e and b create stray light at the focal plane. Source:[22]

Various factors can contribute to stray light in optical systems. These include surface imperfections that cause microscopic scattering, inherent diffraction effects, intrusion of external light, and unintended multiple reflections within the system. Stray light in optical systems can be categorized into two types: ghosts and flare, also known as veiling glare. Ghosts can occur when unwanted reflections within the optical system produce secondary images, commonly known as "ghost images." This phenomenon is often due to light reflecting multiple times between the elements of the imaging system. [23] Flare is a scattered light within the optical system that reduces image contrast. It usually occurs due to imperfections on optical surfaces or of other mechanical elements within the system. External factors like atmospheric conditions, such as fog or sky glow, can also contribute to flare. Light scattering within the optical system or from bright sources within or outside the field of view are common defects. [23]

The presence of stray light can have diverse and prejudicial effects on various types of optical systems. In imaging systems, stray light can diminish contrast, making it difficult to differentiate between distinct features. In analytical systems, such as spectrophotometers, stray light can result in inaccurate readings, thus compromising the integrity of the data. For detection systems, the sensitivity can be adversely affected by stray light, reducing their effectiveness in capturing low-level signals. Similarly, in light projection systems, stray light can produce unwanted bright spots in the beam pattern, affecting the quality and focus of the projection. Controlling stray light is critical in all these applications. Various methods, such as the use of beam dumps like black flocked paper or absorbing glass plates, can effectively trap reflections and reduce stray light. The efficacy of these stray light control methods can be assessed through the instrument's signature. If the signature suggests higher-than-expected scatter, because the stray light is influencing the system's

performance. [21] This effects can be analysed using ray tracing software programs, so that each possible optical path can be examined individually and assessed for potential impact and then if possible rectified.

Chapter 3

Principle of Scatter Measurements

This chapter focus is the standard practice for goniometric optical scatter, this standard serves as a guide for measuring optical scatter from different surfaces with distinct properties. Subsequently, the specific scattering setup employed at Bosch is explored, with an emphasis on the practical aspects of scatter measurement technology. Both the setup currently implemented and a new, large-area setup are presented.

3.1 Standard practice for optical scatter measurements

Standardised measurements of optical scatter, such as ASTM standard E2387-19, are crucial for industry leaders like Bosch engaged in manufacturing and RD, ensuring precise understanding and control of material properties. This standard is essential for maintaining consistency, comparability, and reliability in assessing materials, essential for quality control, product development, and research. ASTM standard E2387-19, developed by ASTM International, presents methods for determining the amount and angular distribution of optical scatter from surfaces. This standard is essential for measuring the Bidirectional Scattering Distribution Function (BSDF), a normalized measure of optical scatter including both Bidirectional Reflectance Distribution Function (BRDF) and Bidirectional Transmittance Distribution Function (BTDF). BRDF analyses light scatter upon reflection, decisive for understanding material reflective properties, while BTDF focuses on light scatter during transmission through transparent materials, essential for studying their transmission characteristics. This systematic approach helps to accurately characterise surface optical properties. [21] BSDF serves as an essential optical parameter for the characterization of a sample's properties, covering characteristics such as gloss, haze, and

chromatic properties. The utility of BSDF measurements extends across a diverse array of material types, including opaque, translucent, and transparent substrates. This large applicability makes the BSDF an indispensable metric for the multidisciplinary areas of material science and optical engineering. These characteristics can be rigorously quantified through the integration of the BSDF function, subject to specified geometric and spectral conditions. The ASTM standard governing BSDF measurements is designed to accommodate an extensive spectral range, covering ultraviolet, visible, and infrared wavelengths. Nevertheless, there exist empirical limitations; for instance, measurements conducted at wavelengths below approximately $0.2 \mu\text{m}$ encounter difficulties owing to constraints in available source and detector technologies. For wavelengths exceeding $15 \mu\text{m}$, diffraction effects become increasingly prominent, thereby influencing the accuracy of the measurements. Materials evidencing fluorescence are explicitly excluded from the reach of this standard. While the guidelines are primarily geared towards flat samples, their applicability extends to those with curved geometries as well. For non-planar samples, the responsibility falls on the user to establish an appropriate coordinate system and define precise beam parameters to maintain measurement accuracy. The standard also provides a methodical framework for approaching measurements; however, it abstains from attributing measured values to specific scattering mechanisms or sources. Moreover, the standard does not provide methods for extrapolating data across disparate wavelengths, geometries, sample locations, or polarizations.

3.1.1 Bidirectional Scattering Distribution Function

The BSDF is a differential function dependent on the wavelength, incident direction, scatter direction and polarization states of the incident and scatter fluxes. It's defined as the surface radiance (L_e) scaled by the irradiance (E_e), which is equal to the power P_s , of the light scattered into the solid angle Ω , normalized to that solid angle, to the incident light power P_i , and to the projected surface area. [21, 24]. Equation 3.1 provides the formal definition of BSDF according to the ASTM standards.

$$BSDF = \frac{L_e}{E_e} = \lim_{\Omega \rightarrow 0} \frac{P_s(\theta_s, \phi_s)}{P_i \cdot \Omega \cdot \cos\theta_s} [sr^{-1}], \quad (3.1)$$

where, θ_s and ϕ_s , denote the polar and azimuthal scattering angles, respectively, while θ_i represents the polar angle of the source direction, defined as the angle between the

source direction and the surface normal. The solid angle Ω , for the receiver, is determined by the geometry of the receiver's aperture stop, as viewed from the center of the sampling aperture. This angle convention has been standardised and is illustrated in Figure 3.1a and Figure 3.1b. E_e is calculated as the average value of the incident power P_i divided by the illuminated area, A . On the other hand, L_e denotes the sample radiance and is calculated as an average value from the scattered power, P_s , collected by the receiver's projected solid angle, $\Omega \cos(\theta_s)$ over the illuminated area A . It is crucial to note that the solid angle Ω and the angular resolution of the system are determined by the geometry of the receiver's aperture and its distance from the sample.

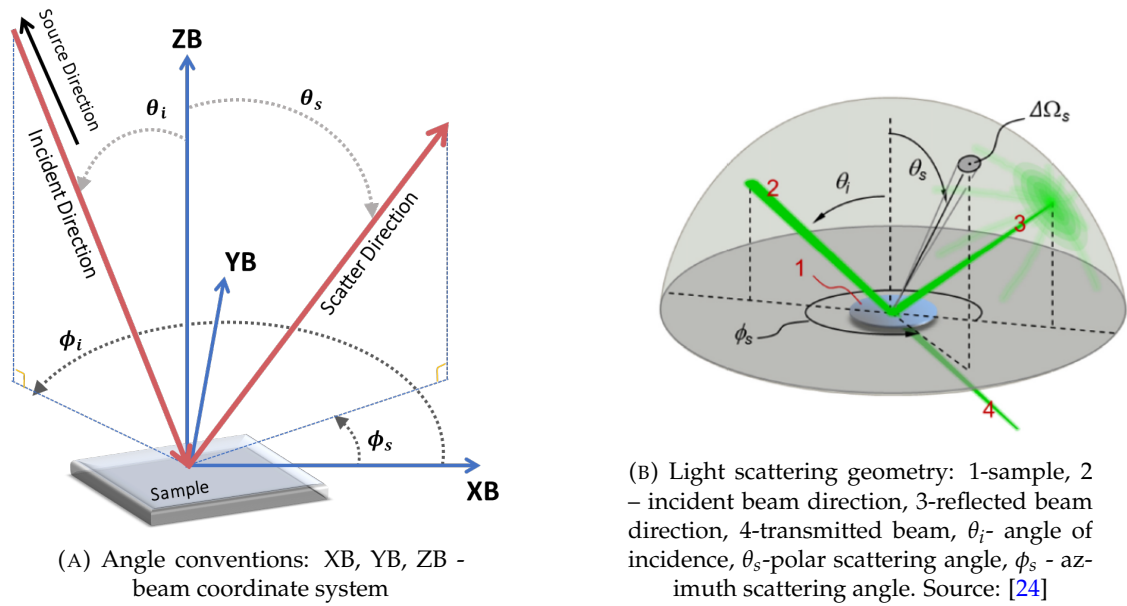


FIGURE 3.1: Detailed angle conventions for BSDF

In conclusion, the BSDF offers insights into various characteristics of a sample. For instance, the BSDF of a Lambertian surface is independent of the scattering direction, manifesting a uniform distribution. In contrast, the BSDF of a specularly reflecting surface exhibits a pronounced peak in the specular direction. For surfaces with non-uniform scattering characteristics across different positions, it is imperative to conduct a series of measurements over the sample area. These measurements must then be averaged to achieve an acceptable level of statistical uncertainty.

Another important function to consider is the Differential Scatter Function (DSF), defined as the fraction of incident light scattered per unit solid angle (see Equation 3.2). The significance of the DSF becomes evident when examining the instrument signature of the BSDF. This is defined as the mean scatter level detected when scattering is present at the

sample, and it is expressed in terms of BSDF. Specifically, the BSDF instrument signature is calculated as the DSF instrument signature divided by $\cos\theta_s$. This means that the instrument signature is dependent on the scattering angle due to its relation with $\cos\theta_s$. If the instrument signature is not below the noise-equivalent BSDF, it will diverge when $\theta_s = 90^\circ$.

$$DSF = \lim_{\Omega \rightarrow 0} \frac{P_s(\theta_s, \phi_s)}{P_i \cdot \Omega} = BSDF \cdot \cos\theta_s \quad (3.2)$$

Instrument Signature of DSF is defined as the mean scatter level detected when no scattering from the sample is present. Serving as an equivalent measure for a perfectly reflecting, specular surface, this signature combines various factors. These factors, such as the size of the incident light beam at the receiver aperture, the diffraction of that beam, and stray scatter from instrument components, are included in the measurement. The DSF instrument signature also depends on the receiver's solid angle and FoV and also quantifies how much light is scattered in a particular direction. For systems with high sensitivity, the scatter levels beneath approximately $10^{-6} sr^{-1}$, the primary limitation, are normally identified as Rayleigh scatter from molecules within the volume of the incident light beam. Two methods are suggested for measuring an instrument's signature. Firstly, by removing the sample and scanning the receiver through the incident beam in a transmission configuration. Secondly, by using a reference sample with significantly lower expected scatter levels compared to the scatter levels of the sample being studied. It is important to use both methods to ensure accuracy. This quantity serves as a crucial metric for evaluating the direction of light scatter. It is crucial to present this information to assess whether the scatter characteristics of the instrument are affecting the sample data. The instrument signature should ideally be several orders of magnitude lower than the sample data to prevent distortion or obscuring of the results. This ensures a clearer and more precise representation of the material or surface under study.

3.2 Experimental setup: design and characterisation

According to the standard, instruments designed to measure the angular distribution of scattered light are founded on three fundamental elements: the illuminator, functioning

as the source of optical radiation; the sample holder, facilitating the placement and orientation of the subject under investigation; and the receiver, responsible for the acquisition and quantification of light scattered in various angular directions. It's important that these three elements are cohesively integrated in a manner that allows a specification of both the incident and scattered directions, thus enabling a collection of the entire spectrum of scattered light.

3.2.1 Illumination System

The illumination system comprises the optical source and other optical elements that illuminate the sample. To ensure that the results are not affected by optical fluctuations, the optical incident power must be monitored. In laser-based instrumentation, the properties of the incident beam are significant in achieving accurate measurements, particularly in applications that require high angular resolution in the scattering direction or near specular beams and diffraction peaks. A converging beam is often used with an f-number greater than $f/20$, and with the focal point situated at the receiver to optimise the angular resolution of the system. Alternatively, if spatial resolution at the sample location is a primary concern, the beam should be focused on the sample. According to the standard, it should be noted that a minimal angle of convergence usually renders any uncertainty stemming from a non-unique angle of incidence negligible. For systems where high angular or sample position resolution is not required, a collimated light beam can be used. In such configurations, the variations in the angle of incidence (θ_i) compromise the integrity of the measurement results. Consequently, the degree of convergence of the incident beam has a direct impact on the signature characteristics of the instrument. Therefore, the degree of collimation or convergence of the beam must be meticulously considered, contingent upon the specific requirements of the measurement system under investigation. To achieve a good resolution of the instrument signature requires careful design considerations, particularly around the off-axis light of the source. In laser-based systems, spatial filters are commonly deployed as the final optical element prior to the ultimate focusing or collimating component. Furthermore, the final directing element, whether it be a mirror or lens, should exhibit minimal scatter characteristics, as this directly influences small-angle scatter and consequently impacts the instrument signature.

Special attention must be given to samples with absorptive properties when utilising high-power laser or infrared light sources. The incident flux may induce thermal effects

that alter the scattering properties of the samples, potentially leading to mechanical distortion or even combustion. Therefore, the sample must be managed carefully to mitigate any damaging effects on sample integrity due to thermal effects. In experiments where high precision is crucial, the application of synchronised phase-sensitive lock-in detection can significantly enhance the quality of scattered light signals. The signals can be modulated through electronic or mechanical instruments, such as a chopper wheel. This methodology effectively improves the signal-to-noise ratio, enabling more accurate measurements. The report of the profile of the illuminated spot on the sample should be taken into account because it serves as a critical metric for assessing the instrument's spatial resolution. Under-illumination of the sample should be avoided; the illuminated spot must be smaller than the receiver's FoV if high spatial resolution is not a requirement. Nevertheless, overly small illumination spots can introduce artefacts into the data due to sample inhomogeneities rather than capturing the average material properties. In the context of coherent illumination, the size of the illuminated spot additionally influences the statistics of speckle patterns.

In conclusion, the design of the illumination system is important for the accuracy and reliability of laser-based measurements. Key considerations include beam characteristics, source regulation, and sample sensitivity, each tailored to the experiment's specific needs. Attention to these details ensures the quality and integrity of the data obtained.

3.2.2 Sample Holder

The sample holder has an important role in ensuring the accuracy and reliability of the optical measurements. It must provide a stable mount that securely fixes the sample, minimizing any potential distortion or movement during measurements. This is important for maintaining a consistent beam geometry with respect to the sample's reference points, facilitating precise alignments and positioning along the $\theta_i, \phi_i; \theta_s, \phi_s$ axes relative to the front surface of the sample. The holder's design should be unobtrusive, ensuring it neither blocks the path of incident or scattered light nor contributes with any stray light that could affect the system's signature. Some advanced sample holders incorporate linear positioning stages, enabling measurements at multiple points on the sample surface, thus providing a more extensive analysis. Manual positioning capabilities, often referred to as Z-motion, are essential for accommodating variations in sample thickness. This feature ensures that the laser spot remains accurately centred on the sample surface, especially

when the incident angle is variable. Moreover, the sample holder should allow for tilting in two directions to orient the sample with respect to the incident beam. The holder, along with the source and receiver assemblies, should be configured in a manner that ensures the incident beam remains centred on the sample when set up at a near-grazing angle. In cases where the source is perpendicular to the sample, the holder should be positioned in such a way that the sample reflects light directly back towards the source. Variations in sample dimensions and geometries may necessitate the utilisation of multiple distinct types of sample holders to accommodate these differences.

3.2.3 Receiver Assembly

In the design of a scattering measurement system, achieving a wide range of scattering angles is essential for broad data acquisition. The detector assembly should be designed and implemented to rotate around at least one axis parallel to the front face of the sample. This configuration allows the system to adjust the scattering angle while maintaining focus on the sample. While the sample itself can be manoeuvred in pitch, yaw, and roll to vary the scatter direction, this approach can complicate the task of capturing scattering beams due to the increased degrees of freedom. This complexity especially manifests when attempting to isolate and analyse the specularly reflected beam. The Receiver Acceptance Aperture provides important information in the BSDF calculation. The acceptance aperture, which essentially defines the receiver's solid angle Ω and consequently also defines the angular resolution of the measurement system. For many systems, where there are no optical elements between the sample and the solid angle defining aperture, the receiver solid angle is given by

$$\Omega \cong \frac{A_{rec}}{r^2} [sr], \quad (3.3)$$

where A_{rec} is the area of the receiver aperture, and r is the distance of that aperture from the illuminated region of the sample. Measuring transparent or translucent samples can introduce variability in the distance r , affecting the uncertainty in Ω and making this relationship particularly complex. The reliability of BSDF measurements can also be compromised by speckle effects, which are characterised by intense and unpredictable variations in scatter, when a coherent light source is used and the acceptance aperture

is too small. To mitigate these effects, it is advisable to take multiple measures. This can be achieved either by averaging over a multitude of measurements taken at different sample locations or by employing dynamic sample movement during the measurement process. This ensures that any features in the BSDF are intrinsic to the sample and not artefacts introduced by speckle. When utilising either the absolute or specular normalisation methods for BSDF measurements, it is necessary to give special attention to the aperture size in relation to the incident beam. An inadequately sized aperture can result in “clipping” of the beam, causing portions of the incident light to go unaccounted for in the incident power measurement. This is a critical oversight as it leads to loss of necessary information, thereby affecting the overall accuracy and precision of BSDF. Hence, ensuring that the aperture is sufficiently large to accommodate the entire incident beam is essential for reaching accurate measurements.

The Receiver is a crucial component that requires careful design and thorough analysis. According to the guidelines, the Field of View (FoV) must include the entire irradiated area A of the sample to ensure that all light is taken into account. This is particularly important when dealing with samples that exhibit diffuse or translucent properties. In these cases, the FoV must extend beyond the direct area of illumination to account for light that is emitted from other positions because of the nature of the sample and scattering. For large incident angles, the study of FoV becomes more complex because the illuminated area distorts into an elongated shape. In such cases, the FoV should be engineered to accommodate this distortion, thereby facilitating precise measurements regardless of the angle of incidence. It is also important that the measurement of the FoV be conducted by deploying a moveable diffuse light source in the X-Y plane and tracking the receiver signal in the Z direction in order to verify if the FoV is always aligned with the sample. The field of view is not only determined by geometry but also by the design of the receiver and the uniformity of the detector element. To prevent inaccuracies due to detector inconsistencies, it is crucial to perform precise measurements.

The Receiver Detector should have good linearity across the entire signal range. This linearity ensures that the optical power and the measured signal are correlated. Both the amplifier and detector should be calibrated together to ensure accurate measurements. The detector’s response time should be shorter than each step’s duration of measurement for accurate data acquisition. Also, when a broad-band source is used, the spectral sensitivity may impact the results. Achieving uniform sensitivity across the measurement area

is important for the detector, which can be obtained by using additional optics, such as integrating spheres or non-imaging optics. In conclusion, the use of an optical bandpass filter on the detector may be necessary to minimise the acceptance of background light. The use of extra optical components, such as lenses or mirrors, in the beam path between the sample and the receiver detector necessitates careful consideration due to their potential impact on the system's performance. Specifically, any optics situated between the sample and the receiver acceptance aperture can adversely affect the instrument's signature and, more critically, compromise the accuracy of the collection solid angle Ω . Therefore, it is important to evaluate the position and types of optics used, it is very important for the optics being positioned between the receiver acceptance aperture and the receiver detector, they often serve the valuable function of controlling the light and defining the detector's FoV. However, these optical components must be clean without any impurity, especially when utilizing absolute or specular normalization methods to determinate BSDF, because unclean optics can introduce variations in collection sensitivity across the collection solid angle.

Proper alignment of the source, sample, and receiver assemblies is essential for obtaining accurate BSDF measurements. A particular issue occurs when the receiver is not properly rotated around the sample face, causing the receiver's FoV to deviate from the illuminated area. This misalignment results in the measured signal to be lower than it should be. Although a system alignment may not be required on a daily basis, but regularly verify the alignment of all movable components to ensure the reliability of the measurement process is necessary. Stray light, which can result from laboratory or instrument reflections, should be meticulously mitigated using beam dumps such as black flocked paper, absorbing glass plates, black box or similar absorbing structure around all instruments or other specialized materials. The efficiency of these stray light reduction measures can be assessed by examining the instrument signature relative to the Noise Equivalent BSDF and Rayleigh scatter baselines; deviations above these benchmarks are indicative of stray light interference. Furthermore, contamination control is the biggest concern, especially for optically smooth surfaces. The optical setup should be housed in a controlled environment that minimizes the risk of sample contamination during both measurement and handling phases. Ultra-low scatter measurements may necessitate additional precautions, such as the provision of clean, particle-free air and rigorous monitoring to prevent the deposition of chemical vapours onto the sample.

3.2.4 Optical designs

Based on this requirements given by the standard for each principal element [21], in figure 3.2 is displayed the schematics of two different optical setups. While both systems incorporate the essential elements required for measuring scattered light, as previously mentioned, they operate on different functional principles and consequently offer unique sets of advantages and disadvantages.

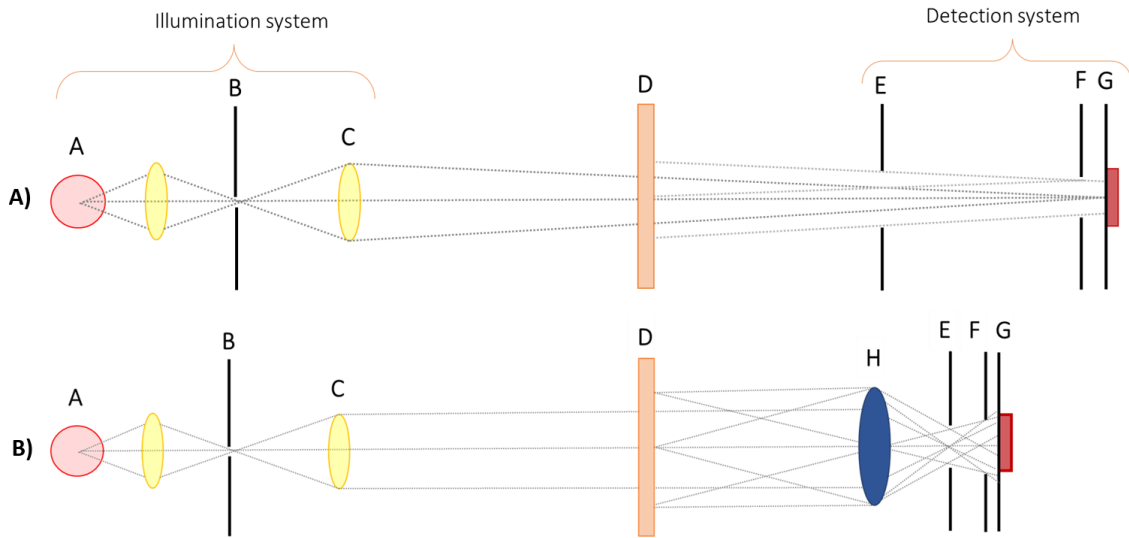


FIGURE 3.2: ASTM standard optical designs for source and receiver combinations: 1-Scattering Setup @Bosch and 2- Large Area Setup. A-Light source ; B and C- Spatial filter ; D- Sample; E-Baffle ; F- Receiver aperture; G- Detector; H- Converging lens. Adapted from: [21]

The configurations are shown in transmission with no aspecular angle, which denotes the viewing angle from the illuminator plane's specular direction to the scatter direction. The optic components are shown as lenses, but these should ideally be replaced by mirrors, as mirrors are generally more achromatic and less prone to introducing stray light, as suggested by the ASTM standard. [21] In Figure 3.2 (A), the optical design is shown, which has been modified for the experimental implementation in the scattering setup at Bosch. This adapted configuration enables accurate optical scatter measurements across different samples.

In this design, a light beam starting from source A is modified by a spatial filter composed of components B and C before it illuminates sample D. The light rays going from the spatial filter to the receiver aperture F can converge or be collimated. In this design, the rays are slightly focused onto aperture F. The detection system captures scattered light

from the sample using a detector (G). The system's FoV is determined by one or more baffles (E), while the solid angle Ω is a function of the area of the receiver aperture (F) and its distance from the sample. This aperture is positioned directly in front of detector G . Typically, the detectors used for measurements in the Visible Light (VIS) and Near-Infrared (NIR) spectral ranges are either photomultiplier tubes or photodiodes. Although auxiliary optics linked to the detector can introduce unwanted scattered light, they are often indispensable for fine-tuning the solid angle or for precisely delineating the detector's FoV. One of the primary advantages of this design lies in its ability to achieve uniform detector efficiency effortlessly, given the absence of any optics positioned between the sample and the detector. However, the design has limitations. For example, it necessitates a large FoV, and the incorporation of baffling E could potentially introduce stray light, especially when laser sources are employed in small-angle scattering experiments. While the baffles could be omitted to mitigate this issue, such an alteration would increase the FoV to the point that stray light may compromise the data integrity of the measurements.

In Figure 3.2 (B), an adapted optical design is illustrated, which has been configured for the realization of a new setup, named "Large Area Setup". Another objective of this work is the development of an alternative system, distinct from the one currently implemented and previously described. Some similarities are observed between this design and the scattering setup currently employed at Bosch, but this has some key distinctions which will be elaborated upon in subsequent sections. The new setup to be implemented was based on the optical design in which the receiver integrates an additional focusing optic, denoted as H , prior to the receiver aperture F . This focusing optic H is designed to project the source aperture B onto the receiver aperture E , thereby conferring the instrument a higher angular resolution, especially when the laser beam of the incident light is highly collimated. Moreover, it serves to image the sample onto the aperture F , such that the aperture E defines the FoV of the receiver. While this optical design has relatively high angular resolution for incoherent light sources, the presence of the optic H between the sample and the receiver aperture F makes it difficult to accurately measure the solid-angle Ω . Additionally, any scatter introduced by optic H unfavourably affects the instrument's performance, particularly in small-angle scattering applications.

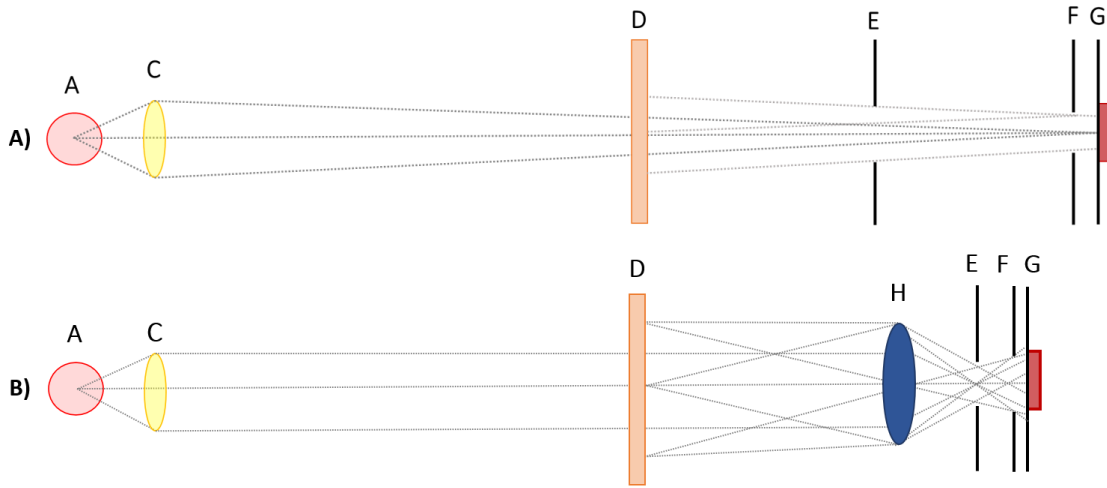


FIGURE 3.3: Optical Path Design implemented at Laboratory: 1- Scattering Setup @Bosch and 2- Large Area Setup. A-Light source ;C- Optical collimator ;D- Sample; E-Iris Diaphragms ; F- Pinhole;G- Detector; H- Converging lens. Adapted from: [21]

As mentioned previously, the designs illustrated in Figure 3.2 were used as a reference. Nevertheless, some modifications have been made. The updated diagrams of the implemented systems are presented in Figure 3.3, which were utilised for measurement activities. The main distinctions between the standard and adapted designs are characterised by the replacement of some components. One of these components was the spatial filter that has been replaced by an optical collimator, this replacement was made by the complex and dense structure of the spatial filter, which could potentially introduce additional stray light due to the incorporation of more optical elements into the system and the use of an optical collimator proved to be advantageous owing to its compact design and ease of integration with the light source, particularly a diode laser. The other significant modification involved replacing the conventional baffle with an iris diaphragm. The modifications implemented in the scattering system have demonstrated promising results, leading to their application in the Large Area setup.

The experimental setups implemented included several key elements: a laser source, an optical collimator, a sample, an iris diaphragm, a pinhole, and a power meter as a detector. Additionally, a converging lens was integrated into the Large Area setup (see Figure 3.3 (B)) to the implementation and study of a sample larger area.

3.3 Experimental Components

3.3.1 Laser diode source

The light source used for the measurements is an SM Fiber-Pigtailed Laser Diode (LP915-SF40 - 915 nm) from Thorlabs, as illustrated in Figure 3.4. The selection of the laser's wavelength, 905 nm, was taking into account by considerations shown in Section 1.2.2. To regulate the operating parameters of the laser, a specialized laser diode controller is utilized. This controller [25], allows the control of the laser's operating current, stabilizes the diode temperature, provide a high degree of output stability, and prolong the life of the diode.



FIGURE 3.4: SM Fiber-Pigtailed Laser Diode. Source: [26]

In the table below, the key specifications of the Single Mode Fiber-Pigtailed Laser Diode, as well as those of the single mode fiber, are presented.

Single Mode Pigtailed Laser Diode: LP915-SF40 [26]	
Optical Output Power	40 mW (Typ.) / 50 mW (Max)
Wavelength	905 nm (Min) / 915 nm (Typ.) / 925 nm (Max)
Operating Current ($P_o = 40$ mW)	130 mA (Typ.) / 200 mA (Max)
Operating Temperature	0 to 50 °C
Fiber: SM800-5.6-125 [27]	
Operating Wavelength	830 - 980 nm
MFD	4.7–6.9 μm @830 nm
Numerical Aperture (Nominal)	0.10–0.14

TABLE 3.1: Principal specifications of the Single Mode Pigtailed Laser Diode and Fiber

3.3.2 Optical collimators

Different optical collimators are required for the various setups to fulfill specific needs. In Figure 3.3 (A), known as the Scattering Setup @Bosch, a smaller area of the sample is scanned compared to other configurations, and the beam is slightly focused towards the detector. For these specific requirements, the CFC5-B Adjustable Fiber Optical Collimator (see Fig.3.5a) is utilized. Non-rotating translation of the housed aspheric lens along the optical axis is enabled by the rotation of the outer barrel of this optical collimator. This design allows for the adjustment of the distance between the lens and the fiber tip, enabling more effective convergence of the beam onto the detector. In the new setup to be implemented, as shown in Figure 3.3 (B), a larger area is scanned. A larger beam is emitted by the optical collimator for this purpose. The C80FC-B Achromatic Fiber Optical Collimator (see Fig.3.5b) is employed in this setup. Due to its larger size, adjustments to the setup have been necessitated, and additional support elements have been utilized to ensure the stability and operability of the optical collimator. A superior beam quality, characterized by a M^2 value close to 1 for single-mode fiber input, is produced by this optical collimator's four-element, air-spaced-lens design. This results in less wavefront error compared to optical collimators with aspheric lenses. The focusing distance of the collimator is adjustable between infinity (the position of the beam when collimated) and the collimator's closest focusing distance.



(A) CFC5-B – Adjustable Fiber Optical collimator.
Source: [28]

(B) C80FC-B – Achromatic Fiber Optical collimator.
Source: [29]

FIGURE 3.5: Implemented Fiber Optical collimators

The key specifications of the optical collimators CFC5-B and C80FC-B are presented in the table below.

CFC5-B		C80FC-B	
f	4.6 (mm)	f	80 mm
NA	0.53	NA	0.25
Input MFD	5.0 (μm)	Collimated Beam Diameter	17.2 mm (@980 nm)
Output Waist ($1/e^2$)	1.00 (mm)	Closest Focus Distance	0.7 m
Max Waist Dist.	462.6 (mm)	Clear Apertured	Ø42.5 mm
Divergence ($^\circ$)	0.062	Outer Diameter	55.88 mm
Fiber-to-Lens Dist.	2.4 - 4.9 (mm)	Transmission	96% at 780 nm
AR Coating	650 - 1050 (nm)	AR Coating	650 - 1050 nm

TABLE 3.2: Collimation Parameters (CFC5-B)

TABLE 3.3: Collimation Parameters (C80FC-B)

3.3.3 Sample holder

The experimental setup requires two separate rotational mechanisms: one to manipulate the sample's orientation the SMALL stage (RS-40 [30]) and the BIG stage (M-060 [31]) to adjust the detector's positioning. These stages are designed to facilitate rotation entirely around a singular, defined axis. An optical post is used to connect the two stages, enabling them to operate as a unified, single-axis rotational system. The detector is placed to the extremity of an extended plate, which is subsequently secured to the rotational platform of the BIG stage. The sample is oriented and aligned with the specified reflection position. Subsequently, the detector will self-rotate step by step during the measurement around the sample to scan the sample and capture the scattered and specular light. This methodology enables a detailed spatial analysis of the sample's scattering properties. The operational principles of this configuration are graphically illustrated in Figure 3.6.

A custom software enables the control of the setup. This interface comprises two C-863 Mercury Servo controllers and a Matlab Graphical User Interface (GUI), created and implemented at Bosch, to simplify the measurement process. The interface is designed for intuitive operation, facilitating real-time manipulation of both the BIG and SMALL stages. It offers control over stage positioning as well as rotational velocities. Additionally, the

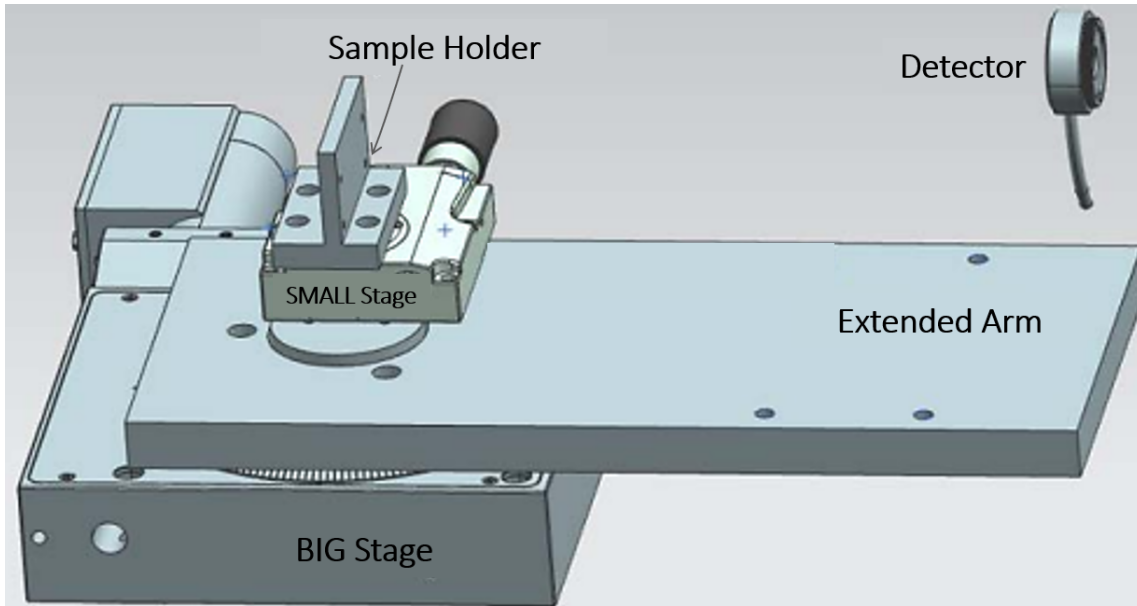


FIGURE 3.6: Mechanic Design: two different rotation stages for the sample holder and detector
Adapted from:[32]

interface provides real-time monitoring capabilities, displaying both the power values and a graphical representation of the power as a function of the detector angle.

3.3.4 Iris Diaphragms and Pinhole

In the current scattering setup, two types of variable irises have been implemented. The first is positioned in front of the optical collimator for the purpose of system alignment, while the second, acting as a substitute for the baffle, is placed before the pinhole. The iris diaphragm, equipped with an adjustable circular aperture, helps to regulate both the size and shape of a laser beam. By altering the aperture size, the laser beam's diameter is effectively controlled. Additionally, the limiting function of the iris diaphragm effectively mitigates the appearance of stray light, reducing undesirable interference in the experimental setups. Overall, the iris diaphragm is an important tool for controlling the size, shape, and propagation of a laser beam. Importantly, the iris used in the experiments has an aperture of 1 mm, which is approximately the size of the laser beam itself. The pinhole, which remains constant across both setups, features an aperture of $400\ \mu\text{m}$ and is positioned in front of the detector. This element defines the solid angle for the experiment. Pinholes are important in laser and scattering systems as they act as high-pass

spatial filters, the appropriate size of this component ensures a equilibrium between signal intensity and noise reduction. The diagrams below depict the iris and pinhole utilised in these setups.



FIGURE 3.7: 400 μm Pinhole Source:[33]



FIGURE 3.8:
Post-Mounted Iris.
Source:[34]



FIGURE 3.9:
Lever-Actuated Iris.
Source:[35]

3.3.5 Detector

The detector used in the measurement is a Photodiode Power Sensor(see 3.10). Its working range covers the wavelength of the laser source. The distance between the sample and the detector along with the pinhole aperture determines the resolution of the setup.



FIGURE 3.10: Photodiode Power Sensor. Source:[36]

The key information of the detector S120C is presented in the table below.

Silicon Photodiode Detector Specifications	
Detector Type	Silicon Photodiode
Wavelength Range	400 - 1100 nm
Optical Power Working Range	50 nW – 50 mW
Max Average Power Density	20 W/cm ²
Max Pulse Energy	20 μ J
Linearity	$\pm 0.5\%$
Resolution	1 nW ¹
Measurement Uncertainty	$\pm 3\%$ 440 – 980 nm
Response Time	$< 1 \mu$ s
Input Aperture	$\varnothing 9.5$ mm

TABLE 3.4: Parameters of the Photodiode Detector: S120C

3.3.6 Lenses

In the Large Area Scattering setup, four different lenses were used to measure system performance, with their characteristics represented in Table 3.11. These lenses were chosen for this study because they offer a broad range of focal distances, allowing for a wide investigating of the setup. For the lens with a focal distance of 300 mm, two different types were used: a singlet (LA1256) and a doublet (ACT508). As anticipated, in the simulations

is possible to see the doublet exhibited fewer spherical aberrations, with the majority of rays converging at a single focal point.

Lens	LA1401-B ⁽¹⁾	LA1979-B ⁽²⁾	LA1256-B-ML ⁽³⁾	ACT508-B-ML ⁽⁴⁾
Diameter (mm)	50.8			
Focal Length (mm)	59.8	199.3	300	300
Back Focal Length (mm)	49.1	195.3	296.6	291.4
Radius of Curvature (mm)	30.9	103	154.5	⁽⁴⁾
AR Coating (nm)	650-1050			
Material/s	N-BK7			N-SK2/N-SF11
Type of lens	Plano- Convex			Achromatic Doublets

FIGURE 3.11: Lenses Parameters: (1).[37]; (2).[38]; (3).[39]; (4).[40]

The description of the elements in each setup is essential for the accuracy of simulations executed in Optical Studio. For specific elements, the identification of appropriate and equivalent replacements was necessary to ensure a faithful and precise representation of the setups being studied.

Chapter 4

Optical systems design: characterization and simulation

A fundamental part of this work centres on characterising and simulating scattering systems. This chapter addresses these important tasks, starting with primary considerations related to the setups. The chapter then outlines the simulation procedures executed using OpticStudio, a leading optical software package. The design of optical systems requires modelling and accurate design to ensure that specific parameters are chosen to accurately represent the experimental components. Therefore, each requirement associated with the scattering setups will be explained and characterised. Subsequently, we will introduce the setups that guided the lens selection for the newly developed system and present the ray tracing and detector viewer produced, a technique that is consistently used in the simulation work.

4.1 Scattering Setup @Bosch

The scattering measurement system at Bosch was characterised by analysing and simulating a diverse set of parameters, which included inter-component distances, various pinhole and iris apertures, and different types of scattering. The system's main features, principles, along with the contribution of each element, were essential aspects to be understood to carry on this study. Consequently, the basic principles of OpticStudio (Zemax) needed to be comprehended in order to carry out the study. For a reliable and precise study of scattering effects, simulations were conducted in the Non-Sequential mode. This mode is particularly suited for examining scattering, diffraction, and optical interferences,

such as stray light analysis, where light interacts with multiple surfaces. The use of the Non-Sequential mode was essential in ensuring the accuracy and dependability of the scattering studies. Consequently, all the simulations presented in this chapter were executed in the non-sequential mode.

4.1.1 Description of the experimental setup

In this study, the experimental setup used at Bosch for studying and characterizing scattering phenomena is pre-designed and implemented. This setup is an adaptation of the design outlined in the standard ASTM E2387-19, as shown in figure 3.2 (A). Details of the setup and its components are explicated in subsection 3.2.4. Additionally, figure 4.1a illustrates the setup in reflection mode. The elements included in the scheme are labelled as follows: A Single Mode Pigtailed Laser Diode (A) is used as the light source, which is slightly focused on the detector (F) by a collimator CFC5-B (B). The sample (C) is illuminated by the light, and is reflective in the cases studied. Light characterization of the sample passes through an Iris (D), determining the Field of View (FoV) of the system. Subsequently, light passes through a pinhole (E), with its area and distance to the sample defining the system's solid angle. Finally, light is detected at various angles, θ_d (detection angle), by the detector (F). This configuration allows for analysis of both the sample and scattering phenomena.

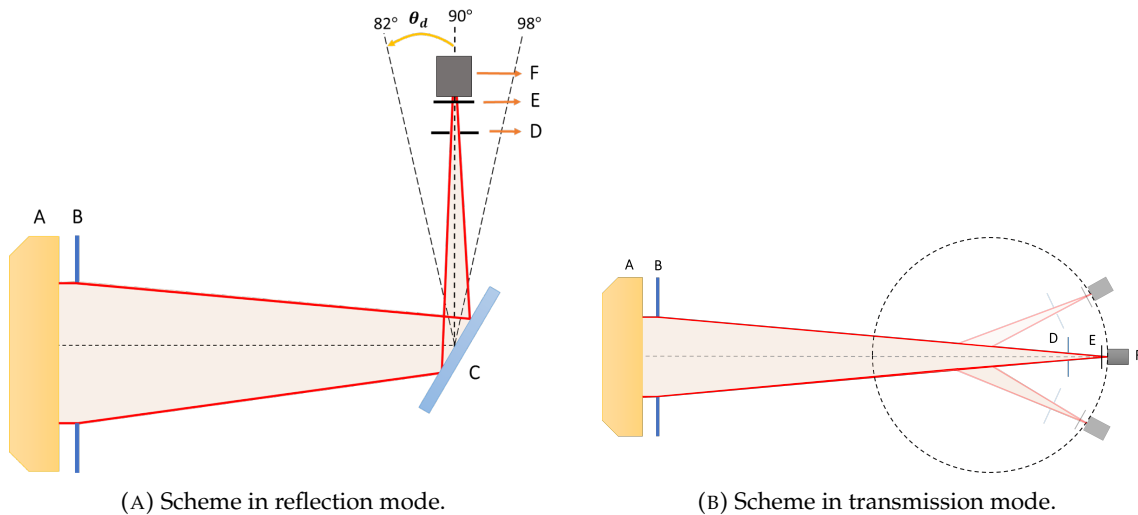


FIGURE 4.1: Scattering Setup @Bosch diagrams.

To control possible variations in the laboratory measurement environment, in the beginning of the samples measurements, reference scans of the laser were conducted over

a range of angles from $\theta_d = -8^\circ$ to 8° . This methodology is depicted in Figure 4.1b and aims to accurately determine the instrument signature. Deviations due to stray source light, optical aberrations, and other contributing factors were systematically monitored [12].

4.1.2 Optical Path Analysis in Zemax

The optical path was characterised using Zemax, to simulate the scattering setup employed at Bosch. Whenever available, the optical elements zemax files were used. The laser element used was the Source Gaussian model as recommended in the Zemax documentation. This model is described to mimic a Gaussian distribution of rays originating from a point source [41]. Parameters for the Source Gaussian model were determined based on the specifications of the utilized single-mode fiber, designated as SM800-5.6 (as shown in Table 3.1). Specifically, the beam size, characterized as the beam radius at the $1/e^2$ point in intensity mostly called MFD (mode field diameter), and the position, defined as the distance from the apparent point of divergence to the source plane, were calculated in appendix B. The values considered were: beam size = $2.9 \pm 0.55 \mu\text{m}$ and position = $0.0289 \pm 0.0619 \text{ mm}$.

In the experimental setup, two key aperture components were used: an iris and a pinhole, both characterized in Zemax as annular objects. The iris was configured with an aperture radius of 0.5 mm, while the pinhole was specified with a radius of 0.2 mm. For signal acquisition, the rectangular detector was used, measuring 0.2 mm $\times$ 0.2 mm in half-width for both X and Y axes. This detector was equipped with 100 pixels along both its X and Y axes, maintaining the same spatial resolution in each dimension. Following the collimator in the optical path, a rectangular sample that could have different types of scattering was positioned. To support the required angular rotations and scans, pivot points were established at two distinct locations within the simulated design. The first pivot point was designated for the sample, while the second served the detection portion of the system. The second one consisted of the iris, the pinhole, and the detector. The detection portion was enclosed within a tube, initially coated with an absorptive material. Therefore, the internal coating of the tube was replaced with a mirrored material. This modification aimed to analyse the potential internal reflections and to conduct a more exact analysis of stray light phenomena within the system.

4.1.3 Setup characterisation

To study the incoherent intensity data from different detectors of the Scattering Setup @Bosch, the NSDD operand was used (see Fig. C.1) in OpticStudio's Merit Function. This operand is highly adjustable and allows the study of specific parameters like distances between elements as well as pinhole and iris apertures under both scattering and non-scattering conditions. The Merit Function was divided into two parts for a detailed study. In the first part, all detectors are cleared before a non-sequential ray trace (NSTR) is carried out without scattering. Following this, the total power is measured using the NSDD operand, setting Pix#:0 to capture the total flux in position space, and Data is also set to zero. The second part follows the same procedure but includes scattering effects by adjusting the NSTR parameters. When the NSDD operand is used in the Universal Plot 1D and 2D. This combination allows for a thorough investigation of various metrics, including the variation of total power with the variation of different parameters, flux values, and statistical measures. This analysis helps to clarify how the optical system performs under different conditions. In the initial study, the efficiency of the system was analysed as a function of the distance between the source and the collimator. This was done to determine the optimal distance between these two elements, to guarantee that the beam is slightly focused on the detector. Figure 4.2 shows both the 1D plot and the detector viewer for each considered distance. From this plot, a distance of 2.941 mm was identified at which the system is slightly focused. This value was subsequently employed in further simulations.

The distances between elements were not subject to additional study, as they had been previously optimized to achieve the angular resolution specified by the solid angle. This configuration was established to meet the primary objectives of the LiDAR project.

4.1.3.1 Beam size and pinhole characterisation

The dimensions of both the iris and pinhole apertures were determined using a similar procedure as in the previous section. Although initial dimensions for these apertures were already defined in the existing setup, additional research was required to validate them due to the significant role they play in beam clipping and the preservation of important laser-based information. To identify the optimal pinhole size for the system, a simulation was carried out with the radius of the pinhole aperture as the changing variable. This

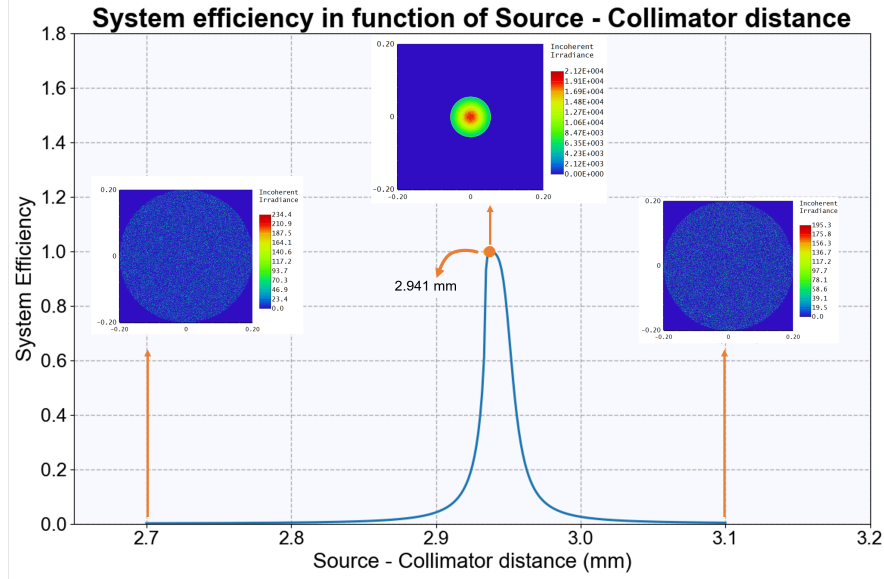


FIGURE 4.2: 1D plot of system efficiency as a function of the distance (source-collimator), based on simulation results and with the detector images for different distances.

procedure allowed for a quantitative exploration of the effects that the change in the pinhole aperture has on important aspects of system performance, namely beam size. The goal of this study was to measure the beam size upon its arrival at the pinhole and to choose an aperture size that retains the fundamental characteristics of the beam without causing information loss through clipping. Since the laser beam has a two-dimensional Gaussian profile, we can obtain the Normalized Power by integrating the profile over the domain defined by the circular pinhole aperture. If we chose a as the pinhole aperture, the dependence of the System Efficiency goes as $f(a) = 1 - e^{-\frac{a^2}{2\sigma^2}}$. A full derivation of this formula can be found in Appendix D. By fitting measured (or simulated) data to this function, we can infer the σ of the Gaussian beam profile.

The suitability of the chosen pinhole size needs to be confirmed with both simulation and experimental validation. Experimentally, we use pinhole apertures of 100, 400, 600, 800, and 1000 μm to measure the Normalized Power with respect to the scattering angle, see Figure 4.3. The laser is slightly focused, exhibiting a beam size at the collimator output of approximately 1mm. The simulation data is obtained for pinhole apertures between 0 and 1mm, in $\frac{1}{300}$ mm increments.

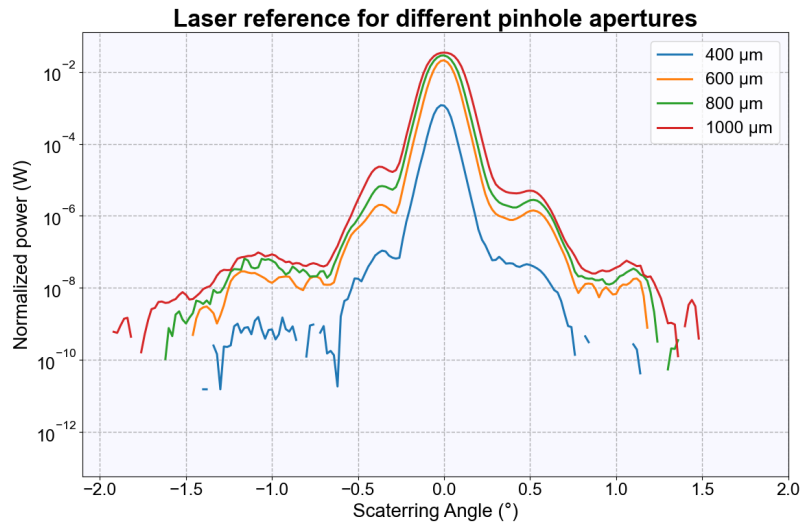


FIGURE 4.3: Laser reference scattering measurements for different pinhole apertures (diameter): 100 μm , 400 μm , 600 μm , 800 μm and 1000 μm

The same dependence can be expected with the pinhole aperture a for the measurements taken with aligned pinhole and detector, i.e., scattering angle of 0° . Such values correspond to the peak of each curve displayed in Figure 4.3. Different type of data, simulation and experimental, were analysed using the same method, by comparing the normalized power for different pinhole apertures for the angle of detection 0° .

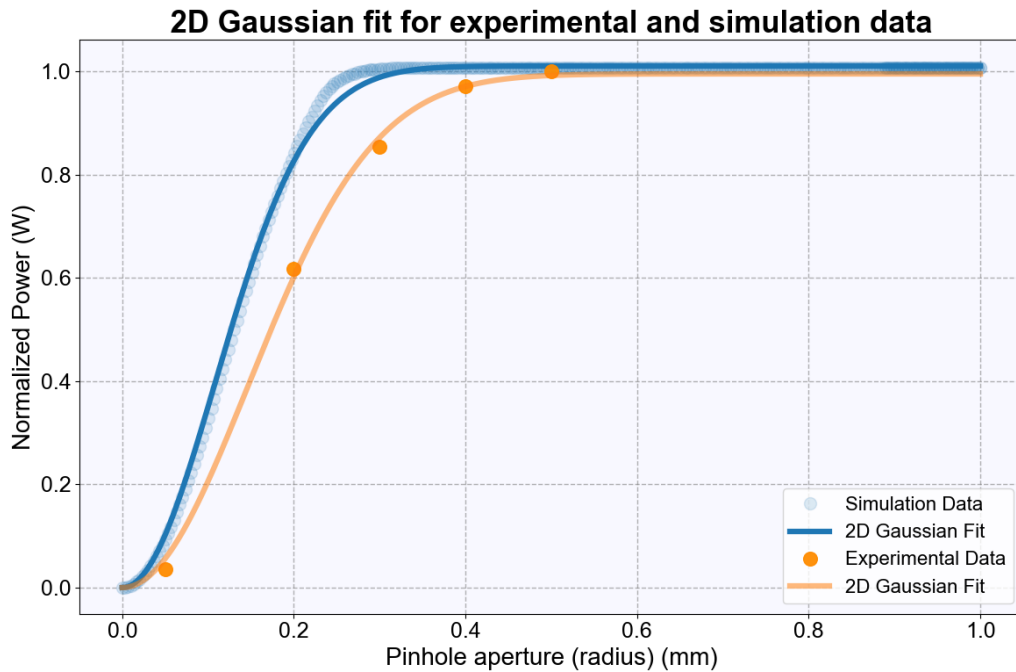


FIGURE 4.4: One-dimensional plot illustrating the power as a function of the pinhole apertures (radius), based on experimental and simulation data.

Fitted Parameters	Experimental data	Simulation data
σ (mm)	0.1468	0.1083
FWHM (mm)	0.3457	0.2551
w (mm)	0.2076	0.1532

The value of σ for the laser beam obtained using the simulation data is $\sigma = 0.1083\text{mm}$. This allows us to obtain the beam diameter ($2w$) at the e^{-2} of peak intensity, using equation D.12, that is approximately 0.3061mm . The selection of a pinhole slightly larger than this dimension ($400\text{ }\mu\text{m}$) was identified as optimal for minimizing the potential beam clipping while still preserving spatial resolution and intensity. Simultaneously, the chosen size was sufficiently small to maintain a high level of spatial resolution.

In other hand, for the experimental data, σ was calculated to be approximately 0.1468mm . This corresponds to a beam diameter of 0.4152mm the e^{-2} of peak intensity. This confirmed the selection of a $400\text{ }\mu\text{m}$ pinhole to minimize the potential for beam clipping while preserving essential laser characteristics.

4.1.3.2 Scattering Effects on System Behaviour

The study, previously mentioned, was also conducted for both mirror and Lambertian samples, illustrated in Figures 4.5 and 4.6, respectively. The aperture size was found to have a significant impact on the samples' scattering measurements. The plots show a proportional relationship between scattering and solid angle, consistent with the theoretical prediction. This comparison examines the proportionate correlation between the scattering patterns at various solid angles.

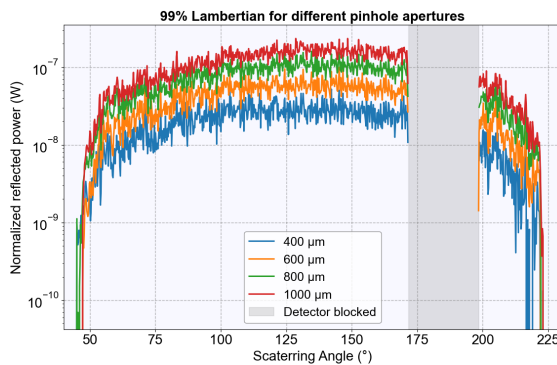


FIGURE 4.5: 99% Lambertian for different pinholes

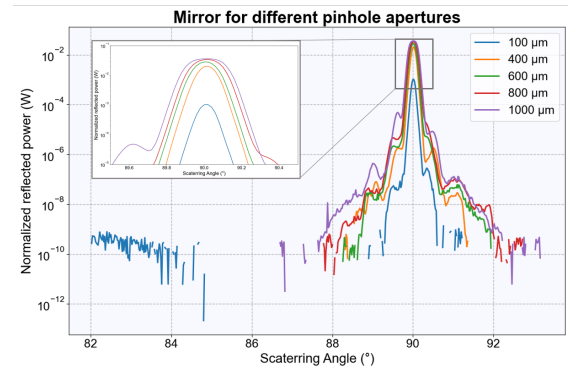


FIGURE 4.6: Mirror for different pinholes

The influence of different values of scattering, in the simulated system, was very important to the characterisation. Scattering properties are defined for each face on an object,

which requires the utilization of some scatter models provided by Zemax, some more efficient than others. Scatter models are defined in terms of a probability distribution function. When OpticStudio scatters a ray, a new direction of propagation is chosen. The direction is chosen to use a probability function and one or more random numbers. The net effect is that if many rays are traced, the resulting scattered ray distribution would approach the probability distribution function. [41] The Zemax scatter model used for this study was the Gaussian scattering defined by:

$$\text{BSDF}(\vec{x}) = A \cdot e^{-\frac{|\vec{x}|^2}{\sigma^2}}, \quad (4.1)$$

where A is a normalization constant. The resulting BSDF is rotationally symmetric. The dimensionless parameter σ controls the Gaussian width. When $\sigma > 5$, the BSDF closely resembles a Lambertian distribution, setting a maximum allowable σ value of 5.

Another parameter introduced is the "Fraction to Scatter". This fraction must be between 0 (no rays will be scattered) and 1 (every ray will be scattered). Simulations were made in which the Gaussian model was applied to a sample in reflection mode (as pictured in Fig. 4.1a). For each set of simulations, and for varying scatter fractions, two-dimensional plots were generated utilizing the merit function operand (15-NSSD), which accounts for scattering in the ray trace. To provide a study into the result of varying scatter fractions on system efficiency, these plots were produced for different pinhole apertures and scanning angles.

The analysis of the data revealed several key findings. Firstly, as anticipated, a decrease in the intensity of the specular light was observed with increasing scatter fractions. This decrease can be attributed to an increase of the number of scattered rays, which led to a decrease in their individual intensities. In addition, a noticeable broadening of the beam profile was recognised as the scatter fractions increased. To explore the relationship between the solid angle and the intensity of both specular and scattered light, data were plotted corresponding to specific scatter fractions—specifically 0, 0.5, and 1. These data points were presented as a function of the square of the aperture sizes of the pinholes, all the while maintaining a constant angle of, 0° and are represented in figure 4.8. This approach was applied based on the understanding that the solid angle is proportional to the square of the pinhole aperture size. Through this analysis, it were provided insights into the influences of the solid angle on the behaviour of both specular and scattered light under various experimental conditions. A further point of significance observed was the

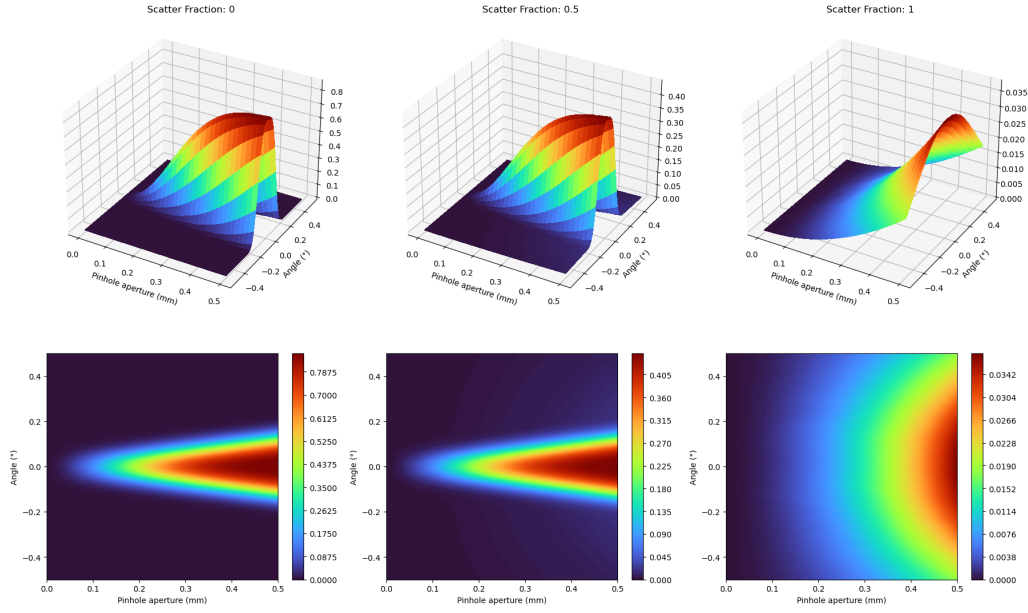


FIGURE 4.7: Comparative visualization of scatter fractions at 0, 0.5, and 1. The top row displays the 3D surface plots, and the bottom row shows the corresponding 2D contour plots. The x and y axes represent the pinholes aperture and the angle of scanning, respectively, while the colour intensity indicates the power of each.

linearity in the data. As depicted in Figure 4.8, a linear fit was found to be reasonable for small pinhole apertures (up to 0.20mm), exhibiting good linearity and a coefficient of determination (R^2) very close to 1. This observed linearity was in agreement with experimental results, thus reinforcing the reliability of the results. Lastly, it was concluded that the efficiency of the system and the aperture size of the pinhole were directly related to the beam size, as was shown previously. So it can be seen that the system limitations were mainly attributed to the beam characteristics rather than sample scattering.

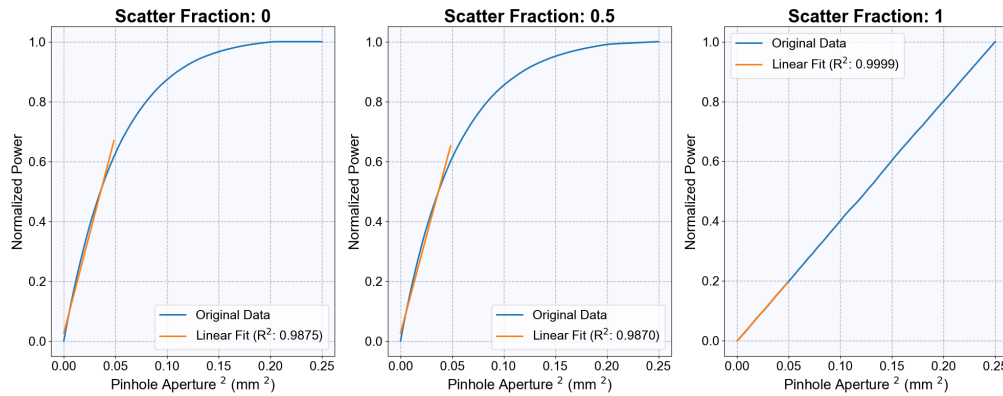


FIGURE 4.8: Normalized power as a function of the squared pinhole apertures (radius), based on the data of figure 4.7 for 0° . From the simulated data in function of different apertures (represented by the blue colour) and the linear fit (represented by the orange colour).

4.2 Large Area Setup

4.2.1 Description of the experimental setup

The experimental setup employed for the Large Area configuration closely resembles the scattering setup previously examined. There are some key differences that were lengthily explained in the chapter. The setup in the reflection configuration is shown in Figure 4.9. Each element within the arrangement is labelled as follows: A Single Mode Pigtailed Laser Diode (A) serves as the light source and is collimated by a C80FC-B collimator (B). The sample (C) is reflective in the studied scenarios and is illuminated by the collimated light. This light is subsequently focused by a converging lens (D) onto an iris (E). Both the detector (G) and the pinhole (F) are positioned at a specific distance from the iris to capture the emitted rays.

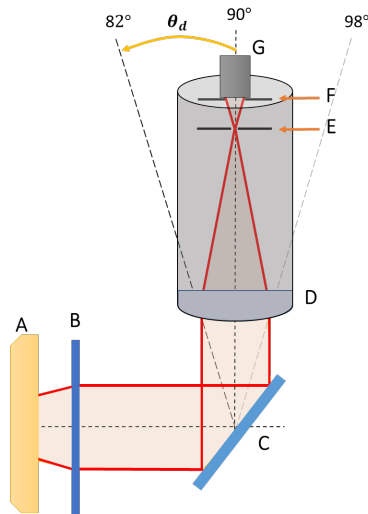


FIGURE 4.9: Scheme of the Large Area Setup in reflection mode.

An objective of this configuration is to scan a large area of the sample. To achieve this purpose, the beam must be enlarged upon reaching the sample, necessitating a change in the collimator. A paraxial lens with an appropriate focal distance was used to emulate a collimated beam. The measurement procedures employed for this Large Area setup are consistent with those outlined in Subsection 4.1.1.

The design of this new setup, was pretty much the same, as the one described for the scattering setup in subsection 4.1.2, the only main difference is that in this new setup, different type of lenses were introduced to the system. In the primary simulation, a paraxial lens was used to determine the perfect focal lens, and then the lenses from the Zemax catalog were used. The primary objective of this Large Area configuration is to facilitate

the scanning of an extensive area of the sample. To meet this aim, the light beam must be expanded upon its arrival at the sample, necessitating a modification to the collimator. During the simulation phase, the Zemax file for non-sequential mode was lacking in pertinent details and appeared merely as a black box. To circumvent this limitation, a paraxial lens with a suitable focal distance was employed to simulate a collimated beam. The measurement techniques utilized in this Large Area configuration remain consistent with those delineated in Subsection 4.1.1. The design architecture, for this new setup, is very similar to the one described for the scattering setup in Subsection 4.1.2. The main difference lies in the introduction of different lens types to the system. Initially, a paraxial lens was used in the primary simulation to ascertain the optimal focal length. Subsequently, lenses from the Zemax catalogue were incorporated into the design.

4.2.2 Characterization of the setup

The focus of the simulation efforts was principally directed towards the determination of the most suitable lens to be integrated into the system. As a result, the characterization of the system was inherently related to the characterization of the lens. Factors such as the optimal focal distance were identified, and relationships between the distances of elements and the apertures of the iris and pinhole were studied. A scheme of the parameters under study, distances, and apertures can be seen in figure 4.10.

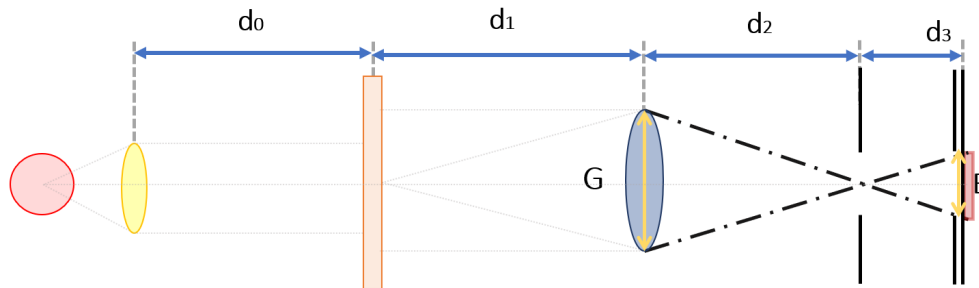


FIGURE 4.10: Schematic representation illustrating the parameters under investigation, including element distances and sizes of lens (G) and pinhole (E).

To achieve the predefined objectives, a ZPL macro was developed. This macro consists of code written in the Zemax Programming Language, also known as OpticStudio Programming Language. The code employed in this macro is detailed in Appendix C and was guided by the Ansys Zemax OpticStudio 2023 R1 User Manual [41], where the

fundamentals and functions of ZPL are described. The parameters collectively contribute to the overall functionality and performance of the optical setup: G , the lens size (which is typically specified by the manufacturer, in this case, Thorlabs, as 50.8 mm), the pinhole aperture diameter (which was 0.4 mm in this case), d_2 (the focal distance of the lens), and d_3 (the iris-to-pinhole distance). This relation between the elements is given by the equation:

$$\frac{E}{d_3} = \frac{G}{d_2} \quad (4.2)$$

This equation serves to provide a mathematical relation for understanding how these parameters are interrelated, thereby facilitating system optimisation. The code varies two parameters: the angle (angle1) of the pinhole and the focal distance (d22) between the lens and the iris. These parameters are sampled over specified ranges, defined by samples for the angle and sample_d2 for the focal distance. To update the optical system, loops iterate through these sampled values. The code specifically modifies the positions (d3 and d22) and orientation (angle1) of various system components for each combination of angle and focal distance. It then triggers a ray-tracing operation to calculate the total optical power, stored as 'flux', captured by the detector at each of these configurations. After the calculations are complete, the code outputs the values of the focal distance, angle, and flux. It also creates a 2D plot to visualise the calculated flux for different combinations of the angle and focal distance, adding a banner for labelling. Overall, this script serves to explore how varying the angle and focal distance in the optical system affects the performance of the detector in capturing optical power.

The result of the plot generated by this macro is represented in Figure 4.11. Due to limitations in experimentation, various values of d_3 were taken into consideration in the simulations. The computed curves, representative of d_2 in relation to different pinhole apertures denoted in radius, were subsequently integrated into the pre-existing macro plot, see Fig. 4.11. These curves were calculated for defined values of d_3 : 1 mm, 2.25 mm, 3.5 mm, 4.75 mm, and 6 mm. For the presented values of d_3 , in the plot of figure 4.11 a region was delineated as having a higher probability of yielding optimal results when combining the four predominant influencing elements: the pinhole size, the fixed lens size, d_2 representing the lens's focal distance, and d_3 representing the distance from iris to pinhole.

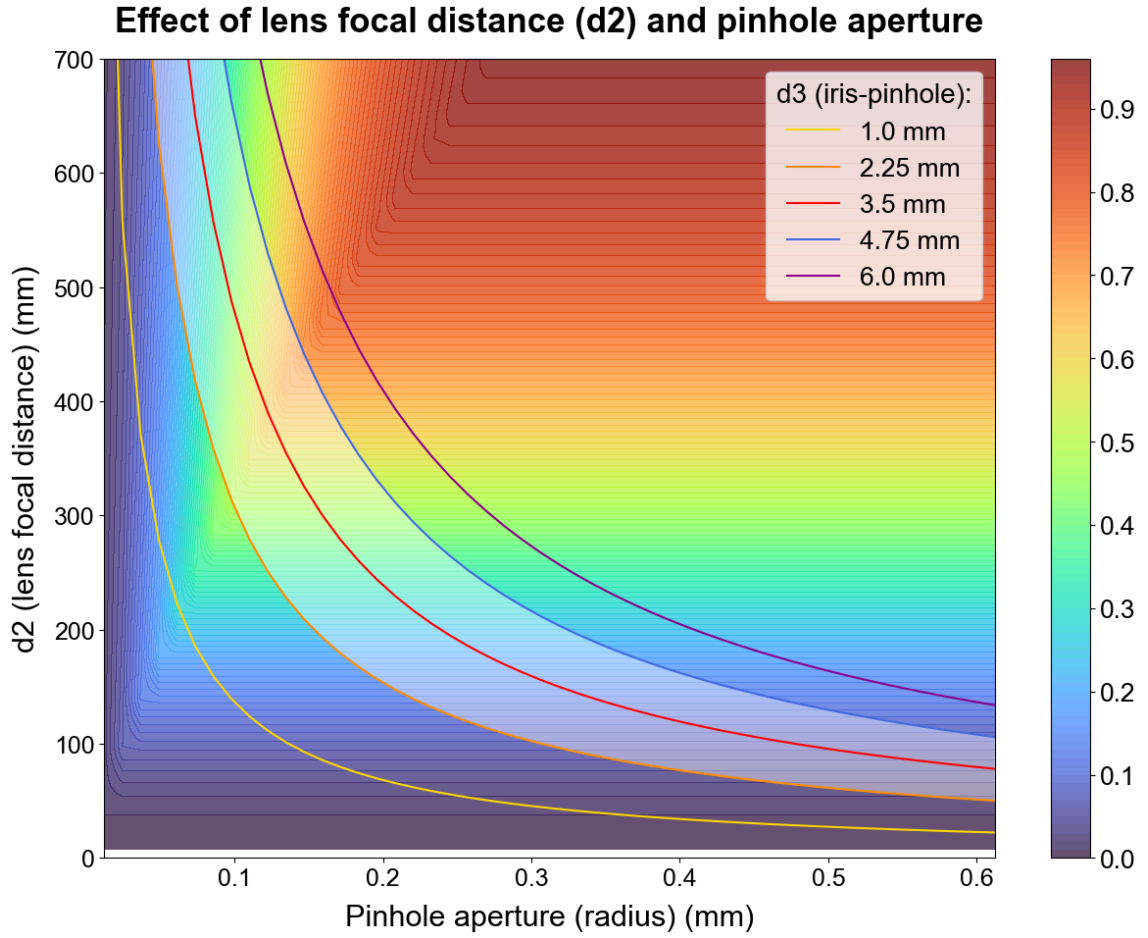


FIGURE 4.11: Contour plot representing the system efficiency as a function of the pinhole aperture size and the focal distance of the lens d_2 . Overlaid on the contour plot are curves representing different d_3 values. The region between the curves for $d_3 = 2.25\text{mm}$ and $d_3 = 4.75\text{mm}$ indicates a higher probability of achieving the ideal setup.

The diagram illustrates the correlation between the pinhole aperture size and the focal length of the lens. It could be concluded that an increase in the pinhole aperture size corresponded to an increase in efficiency, this behaviour was also seen for the focal length of the lens. Within the limitations of the experimental setup, the optimal area was identified in the white region of the graph. Consequently, a lens with a focal distance between 200 and 300 mm was chosen as ideal for a pinhole aperture of $400\text{ }\mu\text{m}$. The upper limit of this range is ruled by the physical dimensions of the setup, since a longer focal length necessitates a larger setup, which makes the measurement process difficult.

4.2.2.1 Large Area setup distances characterisation

The results, presented next, are related to the lens LA1979 (200 mm). The same graphics were made for the other lenses, but the same composition was seen for all lenses. To ensure a more thorough and reliable study, various lenses, each with distinct focal distances of 60 mm, 200 mm, and two with 300 mm—one a singlet and the other a doublet, were analysed. It was observed during the simulations that similar behaviours were evident across the different lenses. The results, to be discussed next, are related to a specific lens LA1979 (200 mm). The same analysis was made for the other lenses, but similar results were observed, so these plots are representative of the performance of all the lenses'. In this setup, there was a need to verify if the distances between elements affected the system efficiency. The simulations were made for the different systems with different lenses, with the varied parameter being the distance between elements, more specific d_0 , d_1 , d_2 and d_3 , these distances are represented in the scheme 4.10. The results obtained for d_0 and d_1 showed that the system's efficiency remains constant for distances bigger than 11.21 mm. However, it's important to note that proper collimation of the beam is required. If not achieved, the system's efficiency could be differently affected by those distances.

Another distance that has studied, was the efficiency of the system with the lens focal distance d_2 , this was a point observed in the experimental procedure (see chapter 5), because there was a need to adjust and study this quantity because of the uncertainty of the exact focal point. With the plot of the Figure 4.12, it can be seen that there is an interval of points, for which the system efficiency is maximum, and for the study of all lenses, it was shown that this distance, differs from the exact focal distance. This was a simulation made after the implementation of the setup, to see if the distance measured in the experimental setup (see Figure 5.16) has the same focal length as the one from the simulation.

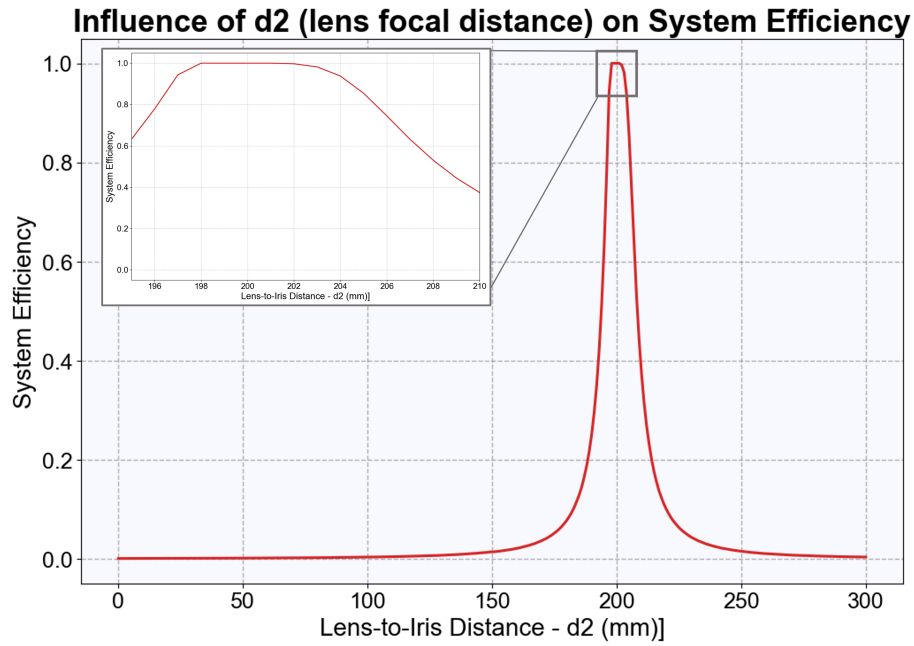


FIGURE 4.12: System efficiency in function of d_2 (lens focal distance) (lens-to-iris distance)

Due to experimental limitations, another parameter that was studied consisted of the distance between the iris and the pinhole and detector (d_3). This distance, within the experimental setup, was determined by the constraints of the used elements and could not be modified. The experimental value of d_3 was 2.93 mm. To ensure that this limitation did not significantly impact the system's efficiency, a study was made on this specific distance. The results from this simulation are illustrated in Figure 4.13.

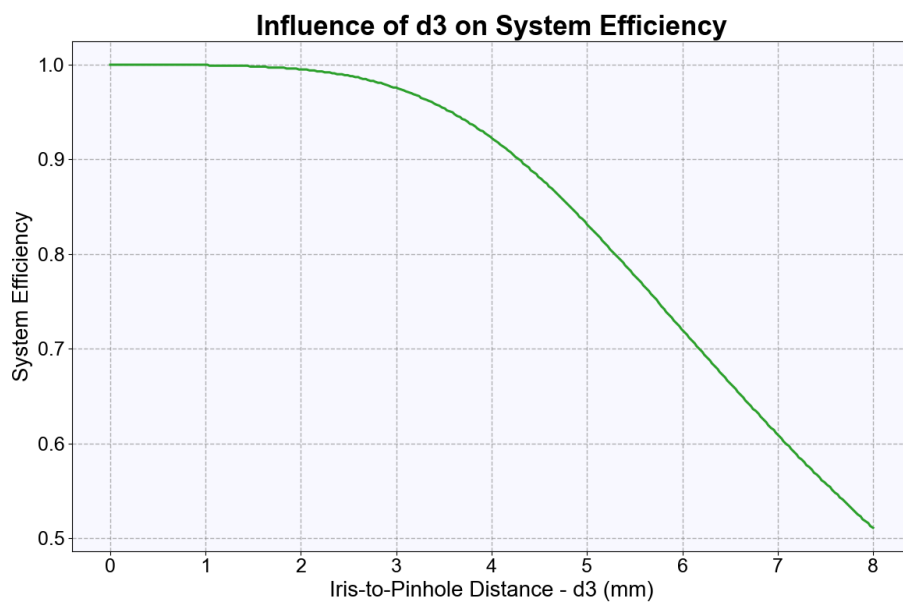


FIGURE 4.13: System efficiency in function of d_3 (Iris-to-pinhole distance)

By analysing the results of the simulation, it can be seen that the efficiency of the system decreases for values greater than 2 mm, but for the measured experimental distance (≈ 2.93 mm) the variation is negligible. So this value can be used without further analysis.

4.2.2.2 Stray light

The following images, taken of the Zemax Non-Sequential Component (NSC) shaded model interface, are representative of several simulations conducted on the setup, including a variety of sample types, each with distinct properties. This study, which covered a different range of samples to which diverse scattering models were applied, was confined to a qualitative analysis. Illustrated in Figure 4.14 is a good example, that utilises a Lambertian scattering model, serving as a representative portrayal of the distinct scattering behaviours observed during the simulations.

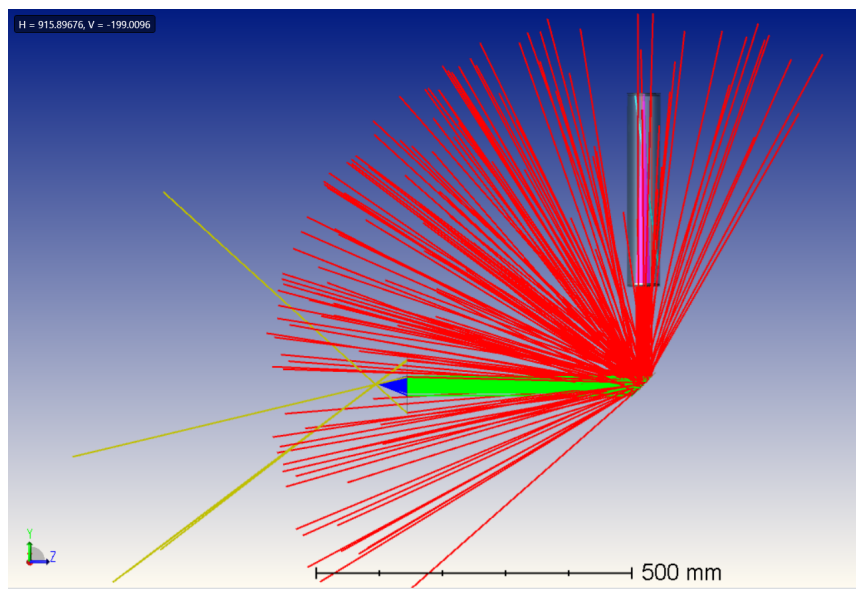


FIGURE 4.14: NCS 3D Shaded Mode: Lambertian Sample

Moreover, the simulations revealed the existence of stray light, which is a phenomenon attributed to the internal components of the setup. Undesirable internal reflections were particularly noticeable within the tube, indicating the complex interactions within the setup, as demonstrated in Figure 4.15. It is evident from the diagram that this occurrence happens for angles of incidence different to 0° . This phenomenon has not been studied in great detail, but it has been seen to affect the results. With a more detailed study, it should be possible to observe the influence that the stray light has on each optical element of the setup, as well as on the measurements.

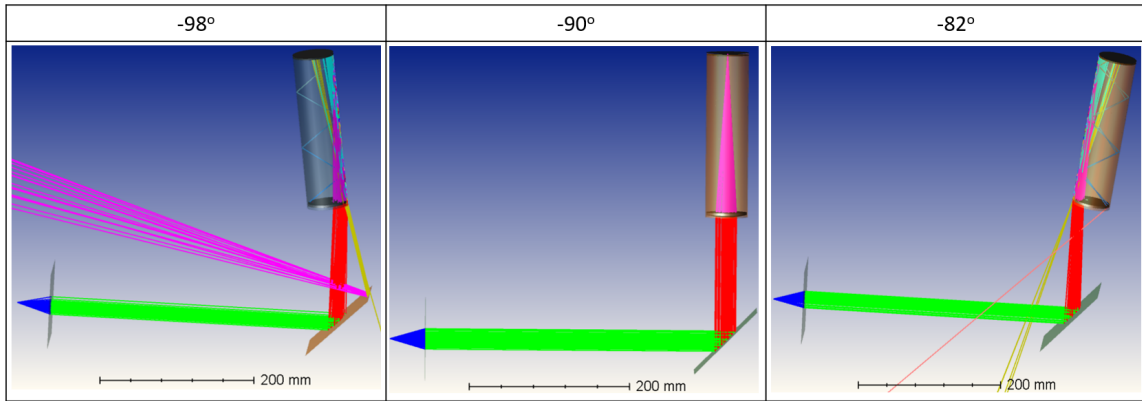


FIGURE 4.15: NCS 3D Shaded Mode: Stray light for scattering angles: 98° , 90° and 82°

4.3 Final considerations

A detailed exploration of the beam size and pinhole was conducted in this chapter, where the precision of the iris and pinhole apertures was examined. It was highlighted that accurate aperture sizes are essential for preserving beam characteristics and avoiding information loss due to clipping. An optimal pinhole size of $400\mu\text{m}$ was determined and experimentally validated, minimizing potential clipping while preserving spatial resolution and intensity, leveraging the Gaussian nature of the laser beam profile. The impact of scattering effects on system behaviour was studied using several models provided by Zemax, with a focus on the Gaussian scattering model. It was observed that increased scatter fractions led to decreased intensity and broadening of the beam profile, influencing the relationship between system efficiency, aperture size of the pinhole, and beam size. The primary limitations within the system were found to be attributed to the characteristics of the beam rather than scattering from the sample. Modifications to Zemax files were performed to explore optimal scenarios within a Large Area configuration, concentrating on identifying the ideal focal distance for system integration, as well the distances from the setup were studied and maximised. This work provided important insights and understanding that are expected to significantly contribute to informed optimisations and refinements in future work and applications.

Chapter 5

Experimental scatter measurements

This chapter will focus on the experimental results. The scattering setups will be assembled, calibrated, and measured. Experimental considerations and steps necessary for each setup are detailed, followed by a description of the system alignment process. The working concepts of key components in the setup are then explored, with special emphasis placed on the large-area configuration. Included in this section are discussions on the positioning of each lens relative to the sample and the different types of sample holders employed. Finally, the experimental results from each setup are presented. In the case of the large-area setup, the behaviour of the lens under different conditions is compared. Also, one of the main goal of this chapter is to compare the results of the large area setup with the scattering setup @Bosch.

5.1 Samples

In this report, experimental scattering measurements and material characterizations were executed on three distinct samples: a 99% Lambertian reflector, a planar mirror, and a polygon-shaped mirror. The respective samples are showed in Figures [5.1](#), [5.2](#), and [5.3](#). To mitigate the chance of surface contamination, all samples were meticulously handled using gloves. This preventive measure ensured that the oils naturally produced by human skin did not interfere with the material properties or the subsequent scattering measurements. The samples utilised in this study were provided by Bosch. The primary objective was to conduct an inclusive analysis of diverse materials with varying coating characteristics. Specifically, the study aimed to elucidate the differences in scattering behaviour of these materials that had different coating characteristics, different shapes and different

reflectivities. All samples examined were opaque, they were placed in a reflective configuration for the experimental analysis. In the case of the polygon-shaped mirror, tests were conducted on its various faces, and measurements were obtained both horizontally and vertically to provide a characterization of its scattering.



FIGURE 5.1: 99% Lambertian
Source: Zenith Lite diffuse targets

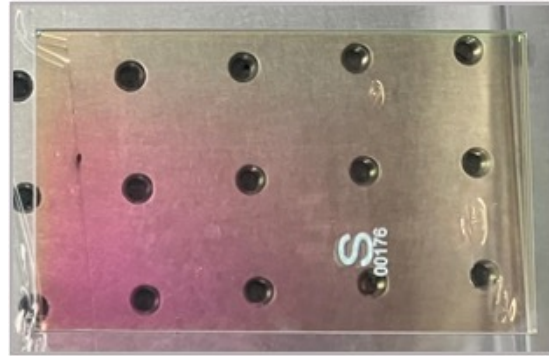


FIGURE 5.2: Mirror
Source: Bosch

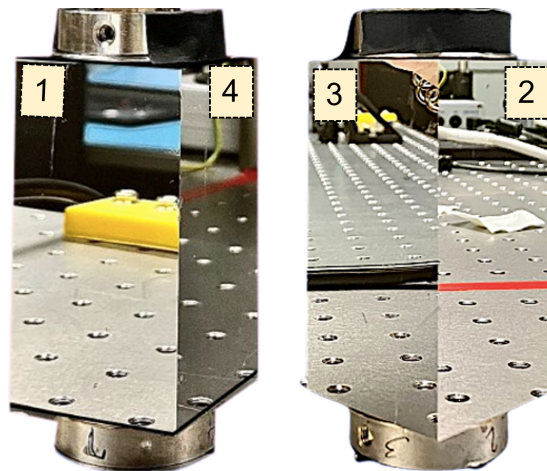


FIGURE 5.3: Polygon mirror with 4 faces
Source: Bosch

The polygon mirror is made from a 6060 aluminium alloy. The distinct specifications and characteristics of this polygon mirror make it well-suited for scattering studies, whereby an understanding of the behaviour of different materials and coatings can be achieved.

5.2 Experimental Setup

A few experimental details must be taken into account during the assembly of the setup to achieve the maximum power intensity and system stability. The experimental work was divided into two distinct phases. The first phase was dedicated to the measurement of the scattering setup @Bosch, while the second phase involved the implementation and measurements using the Large Area setup. Although measurements had already been conducted for the scattering setup @Bosch, additional measurements were also made to ensure uniformity in measuring conditions across both setups. The scattering setup had previously been assembled, the only requirement was to verify the system's proper alignment before each measurement. After the alignment was confirmed, the samples were measured. The designed setup is illustrated in Figure 5.4. The elements used in this setup were already described in 3.2.4 and this configuration was based in the scheme 4.1a.

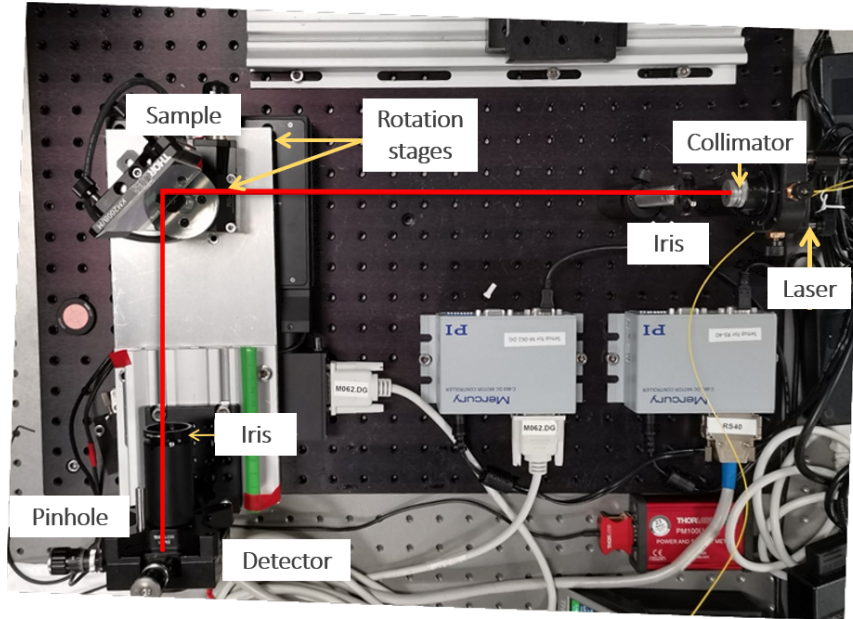


FIGURE 5.4: Scattering Setup @Bosch

The Large Area Setup was subsequently implemented. Due to the characteristics of its components, additional precautions had to be taken for this setup. Due to longer distances used, more support elements were required to ensure and maintain system stability during measurements, according to the focal length of the lens being studied. This procedure had to be carried out meticulously to ensure that, before measurements were

taken, the system remained aligned and the accuracy of the measurements was not compromised in any way. To ensure the system was kept aligned both vertically and horizontally, a system of optical posts and cage systems rods were employed. These were used to connect all parts of the system at a 0° . Once it was seen that the system was properly aligned, the maximum intensity ($\approx 42\text{mW}$) reaching the detector was measured. If this value was not the maximum expected, some adjustments were made to the system until this value was achieved. As mentioned previously, lens tubes were utilized from the lens to the detector in order to minimize the light interferences from the laboratory, despite all measurements having been conducted in a low-light environment. A camera capable of detecting the light was employed so that the optical path could be monitored during alignment and also during measurements. The use of this camera proved to be essential to detect leaks and reflection of the beam on the other optical surfaces. In the following image, a picture taken by the camera can be observed. The represented case occurred during the alignment of the beam on the mirror, with the objective of ascertaining that the beam was entirely incident upon the sample.



FIGURE 5.5: Image captured by the camera during the alignment of the mirror, illustrating the utility of the VIS/NIR Detector Card and the camera in visualising the beam's location.

In this image 5.5, a VIS/NIR Detector Card can also be observed. Similar to the camera, this card facilitated the visualisation of the beam's location, although it exhibited fast saturation. Despite this limitation, when combined with the camera, the alignment process became easier and reliable. For each sample, a distinct setup configuration was employed, as each sample possessed unique characteristics, demanding the adaptation of the sample holder to each one of them. In figure 5.6, the large area setup can be observed, in which no samples are present, and is configured to measure the signature of the laser,

referred to as the laser reference. This measurement is conducted through an angular sweep from -8° to 8° , with a step of 0.02° .

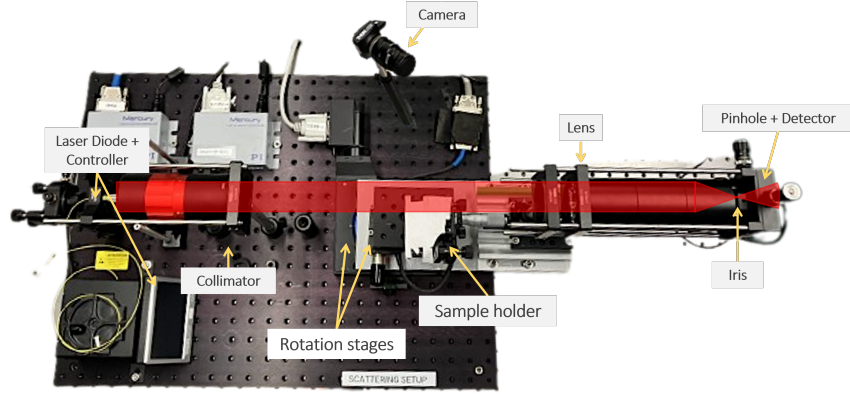


FIGURE 5.6: Laser reference measurement setup

The samples, which included a mirror, polygon, and Lambertian, had to be positioned in the most appropriate sample holder. They were required to be set in reflection mode, at a 45° angle from the collimator. For the mirror's study, the scanning process was carried out from 82° to 98° , with increments of 0.02° . In the case of the Lambertian target, ideally, a 360° analysis would be conducted. However, due to the size constraints of the setup, such a complete study was not possible. Consequently, the angular range for each lens was adjusted based on the same setup limitations. These setups are shown in the next figures.

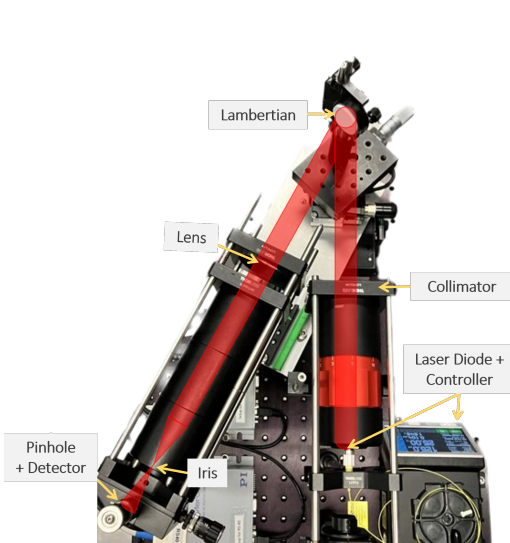


FIGURE 5.7: 99% Lambertian measurement setup

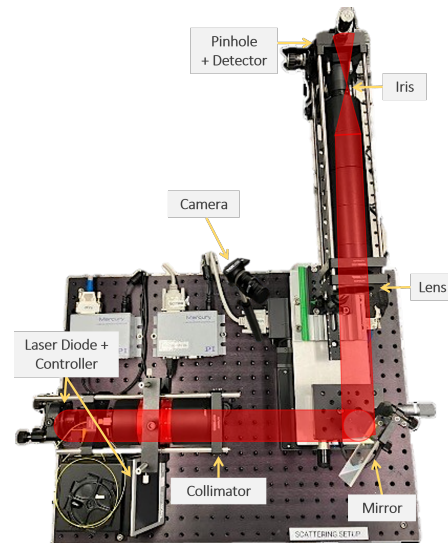


FIGURE 5.8: Mirror measurement setup

For the polygon setup, see Fig. 5.9 the same measurement conditions that were applied to the mirror were also used for the polygon. For this sample, was made, an additional study of each face was performed with it positioned both vertically and horizontally.

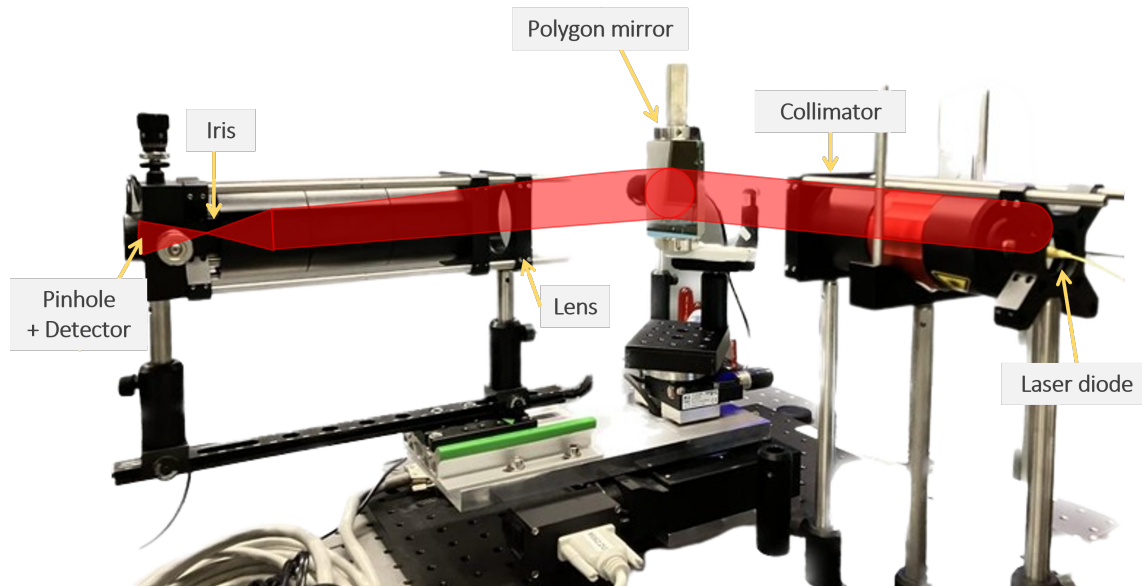


FIGURE 5.9: Polygon measurement setup

5.2.1 Results and discussion

5.2.2 Systems Performance Analysis

In this section, the results obtained for the two studied setups: Large Area and Scattering Setup, will be presented comparatively. The study will present the results for each examined lens for the large area setup. The objective was to determine the most effective lens that would give the best results when analysing a sample. The study was previously carried out in simulations, and the intent of this experimental work was to validate the simulated work. The study conducted for each lens was performed under the same conditions, thereby ensuring the reliability of the results. The laser reference, or light source signature, for each setup can be inspected in figure 5.10. This study was made in transmission mode without a sample. It can be observed that all lenses exhibit their peak scattering intensity at or near 0° , which is typical for specular reflection where the angle of incidence equals the angle of reflection. This suggests that all lenses have a significant component of specular reflection. But the greater the focal distance, the narrower the beam becomes.

The tails of the scattering curves, representing light intensity as it falls off from the central peak, change with increasing angles of incidence. These steeper tails correlate with a reduced scattering effect, indicating smoother lens surfaces and higher optical precision. The variation among the curves for different lenses reflects their respective surface qualities and scattering characteristics. Lenses with the most pronounced slope, such as the LA1256-300mm, suggest superior performance for applications where control of stray light is essential.

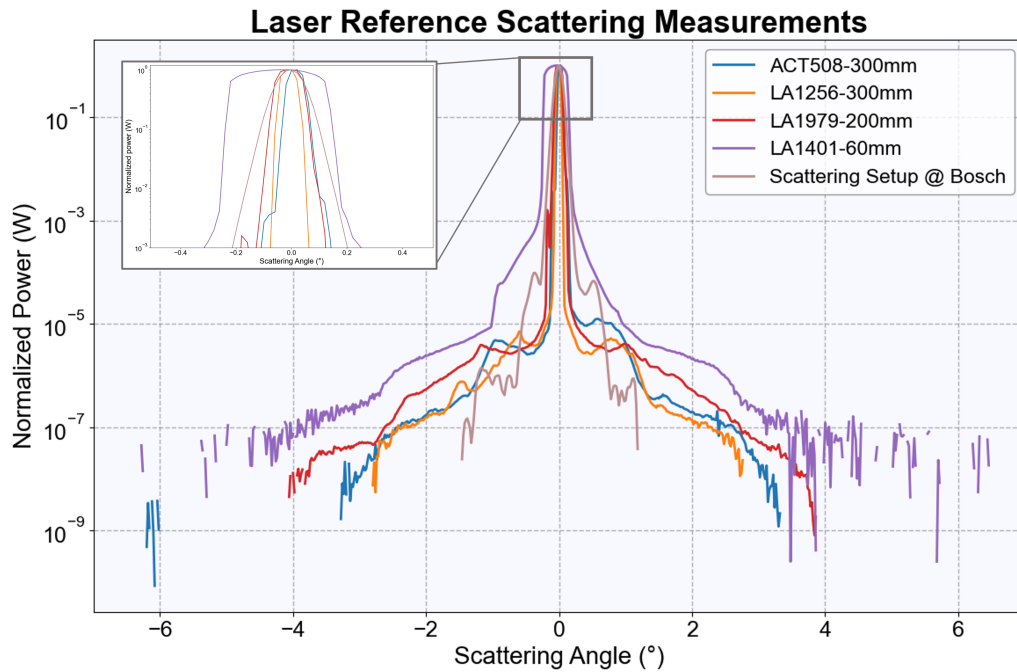


FIGURE 5.10: Laser reference for the Large Area setup and Scattering Setup @Bosch

After measuring the laser signature, a study of the different samples was conducted. The first sample to be measured was the mirror. The results can be analysed through Fig. 5.11. It can be observed that the greater the focal distance of the lens, the higher the intensity of the beam. The greater the focal distance, the narrower the beam becomes at the peak of scattering intensity at 0° . In these measurements, it is possible to observe that some systems were not entirely aligned to 0 degrees, as the existence of a slight angular shift around 0 is evident for almost all the systems.

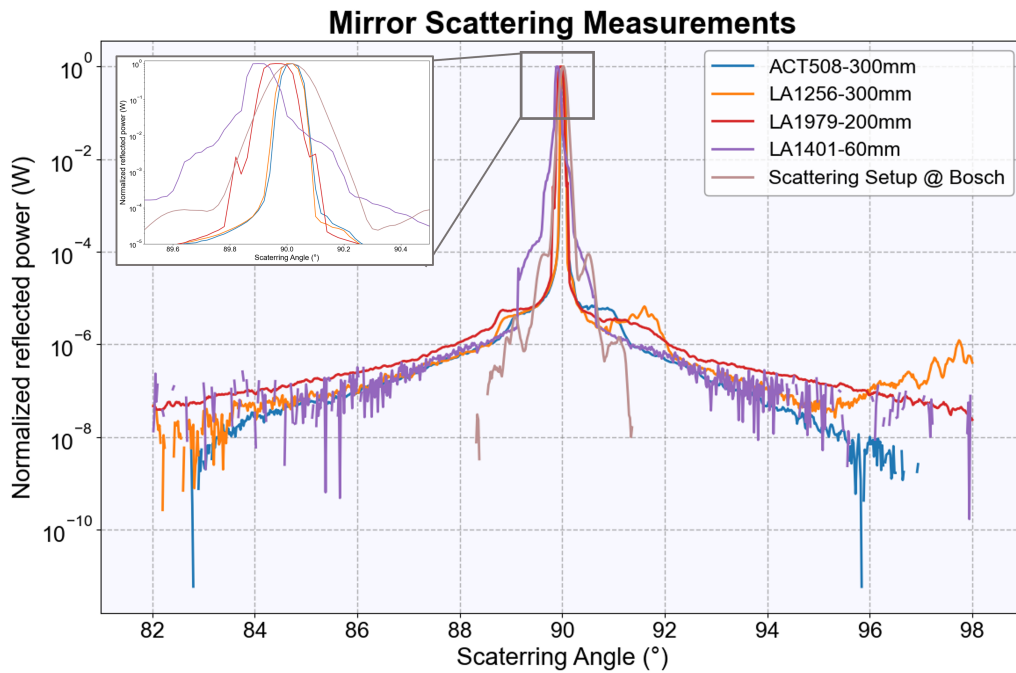


FIGURE 5.11: Mirror measurements for the Large Area setup and Scattering Setup @Bosch

When comparing the results of measurements of the laser reference and the mirror between the @Bosch scattering setup and the large area setup for the different lenses. It is clear that the @Bosch scattering setup reaches approximately half of the maximum intensity value, while the large area setup reaches the maximum intensity value. It can also be observed that the scanning range is more limited, not exhibiting as much scattering at higher angles. As previously mentioned, the study of the polygon with both setups was only conducted for face 2. The results obtained for the different lenses were quite coherent and followed the same pattern, both horizontally and vertically. It was observed that the periodic peaks exhibit different intensities depending on the lens used. The main difference that can be identified is between the large area setups and the Bosch scattering setup. In both horizontal and vertical observations, it is apparent that the scattering setup @Bosch produces more noise during scattering. On the other hand, the scattering in the larger area is clearer, enabling detailed identification of periodic peaks within a certain angular range. This is due to the larger area being scanned, resulting in each point being an average of multiple points. Consequently, it provides more information and increased accuracy. However, the scattering setup is more symmetrical in terms of angular scan, and the peaks can be more easily observed for this setup. For lenses with a focal distance of 300 mm, the peaks exhibit very low intensity, being almost null for higher angles.

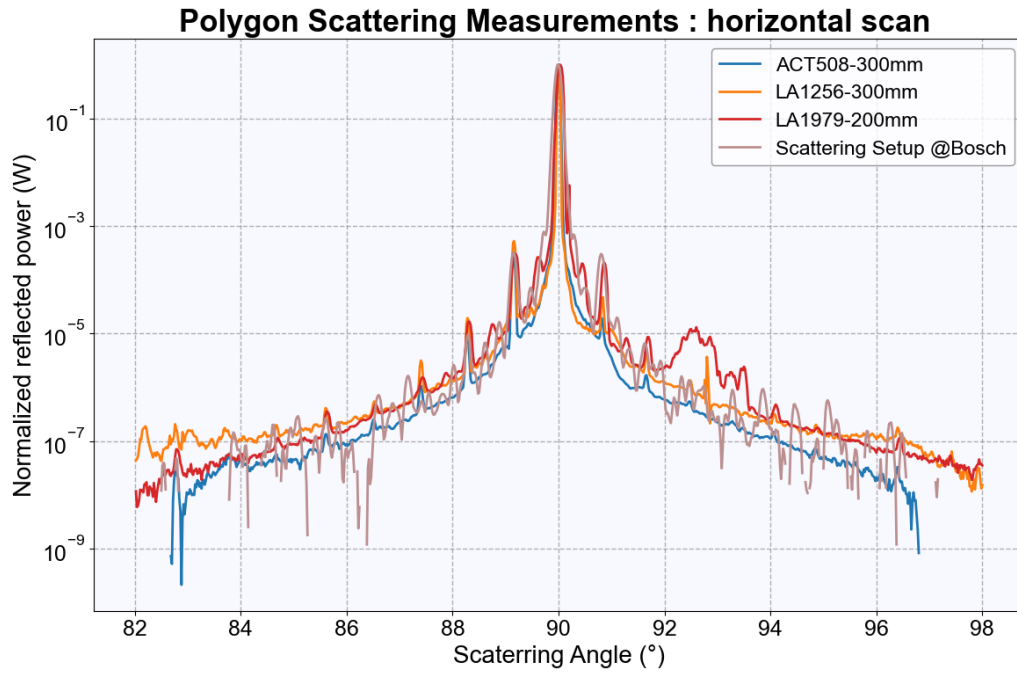


FIGURE 5.12: Polygon (face 2) in horizontal measurements for the Large Area setup and Scattering Setup @Bosch

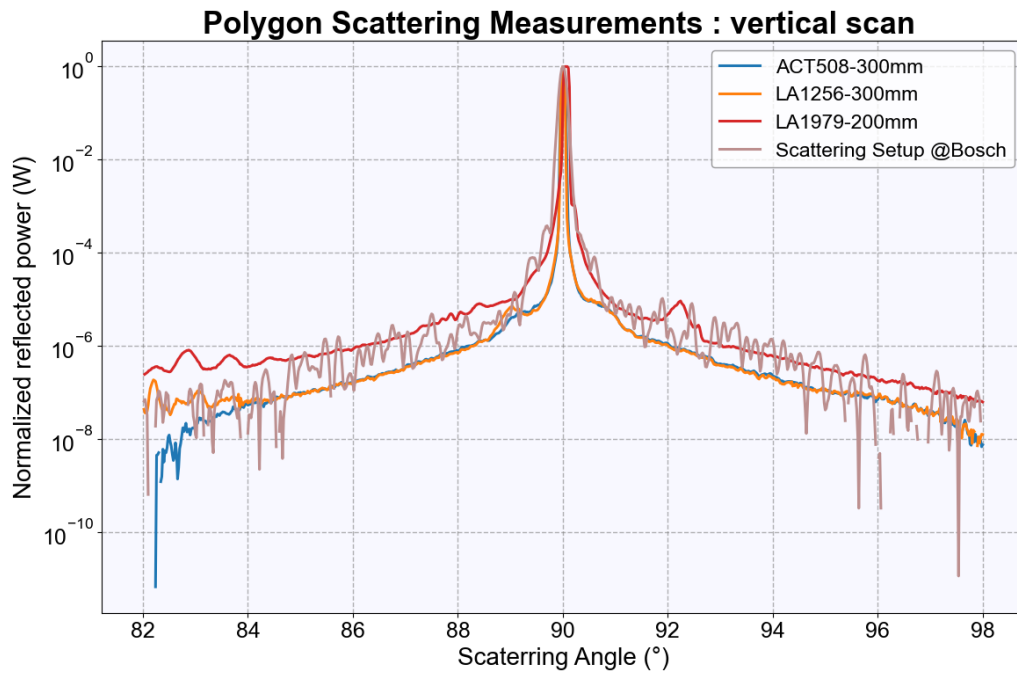


FIGURE 5.13: Polygon (face 2) in vertical measurements for the Large Area setup and Scattering Setup @Bosch

A sample lambertian with 99% reflectivity was also studied, see Fig. 5.14. The measurements for this sample, using the large area setup, were more challenging to conduct

due to the considerable size of the setup. This configuration, large area setup, when compared to the scattering setup @Bosch produces less noisy results, which is good for the analysis of scattering.

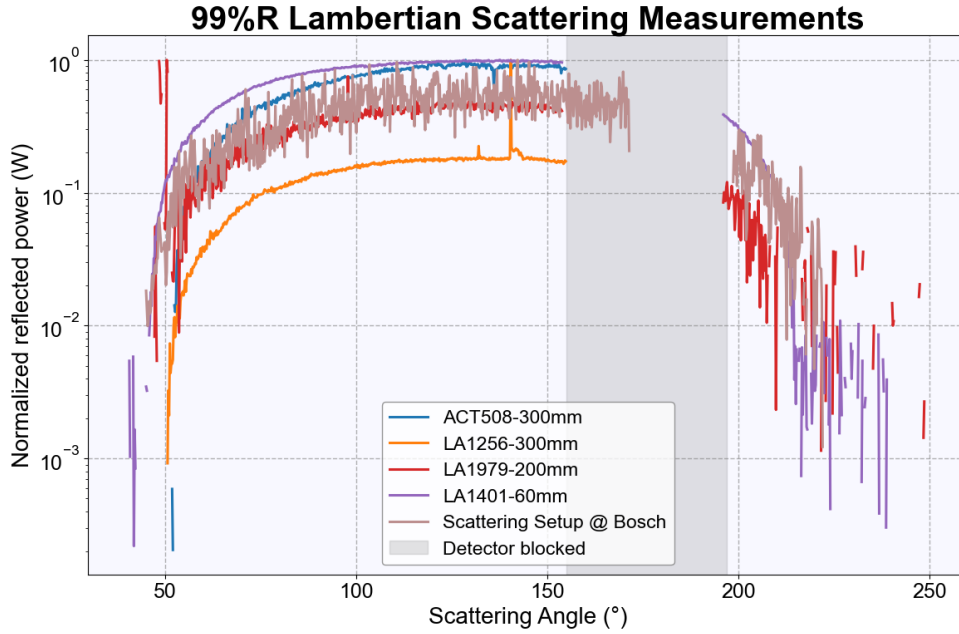


FIGURE 5.14: 99% Lambertian measurements for the Large Area setup and Scattering Setup @Bosch

To calculate the BRDF, this Lambertian could be used to calibrate the setup. Since this measure was not determined, the obtained results only served to facilitate a comparison between the lenses and the setups.

5.2.3 Measurements for Lens- LA1979 ($f = 200mm$)

A more detailed and meticulous study was conducted for lens LA1979, analogous to what was performed in the simulations. For this lens, the distance d_2 was varied experimentally to identify the ideal experimental focal distance. The polygon for this lens was analysed in bigger detail, with all faces of the polygon being examined both vertically and horizontally. After it was verified that face 2 of the polygon contained the most impurities and scratches, the same study was carried out only on this face for the remaining lenses.

5.2.3.1 Lens focal distance characterization

For the study, which had also been performed in the simulations (see Fig. 4.12), the distance d_2 was varied. For each measurement, the distance was increased by 1 cm at a time.

The obtained plot is displayed in a logarithmic scale in Fig. 5.15a, allowing for the observation of the laser output behaviour for the defined angular range -8° to 8° . To analyse the variation in the maximum intensity value, the angular range was reduced; thus, the differences in the maximum for each distance d_2 could be observed and are represented in Fig. 5.15. The distance was altered across 13 values, with 0 representing the initial distance, equivalent to $d_2 \approx 212$ mm.

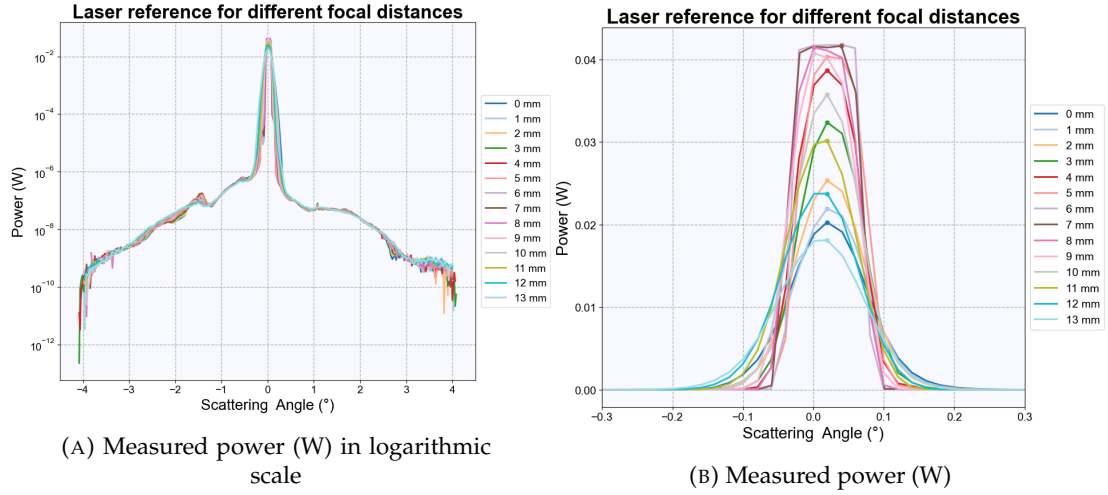


FIGURE 5.15: Laser reference for different d_2 distances

To determine the ideal focal distance for this lens, the maximum value of each curve was extracted, and a plot of these maximum values as a function of the corresponding distance d_2 was created, and can be seen in 5.16.

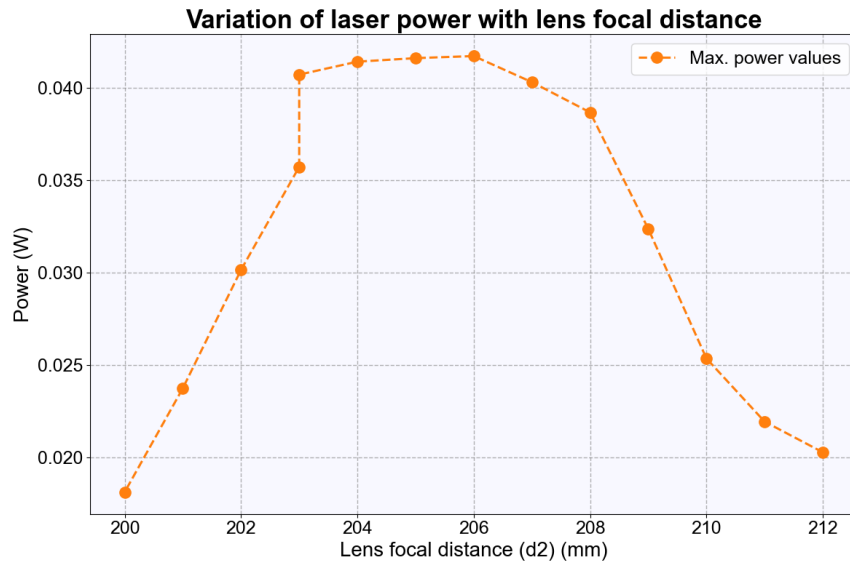


FIGURE 5.16: Study of lens focal distance (d_2)

It was observed that the maximum output ($I \approx 42 \text{ mW}$) was obtained for the distance $d_2 = 206 \text{ mm}$.

This value was utilized for the subsequent measurements with this lens. For the other lenses, this study was also made, and the maximum value was also used for the remaining measurements.

5.2.3.2 Polygon measurement for the four faces

The study of the polygon was done with greater detail for lens LA1979. The polygon has multiple faces, and it was intended to determine whether there were differences among the four faces. Consequently, the study was carried out with the sample positioned both horizontally and vertically. In the vertical orientation, discrepancies among the different faces of the polygon are perceptible, although they are nearly minimal. Additionally, in the graph in Fig. 5.17, it can be seen that the curves corresponding to each face show similar behaviour.

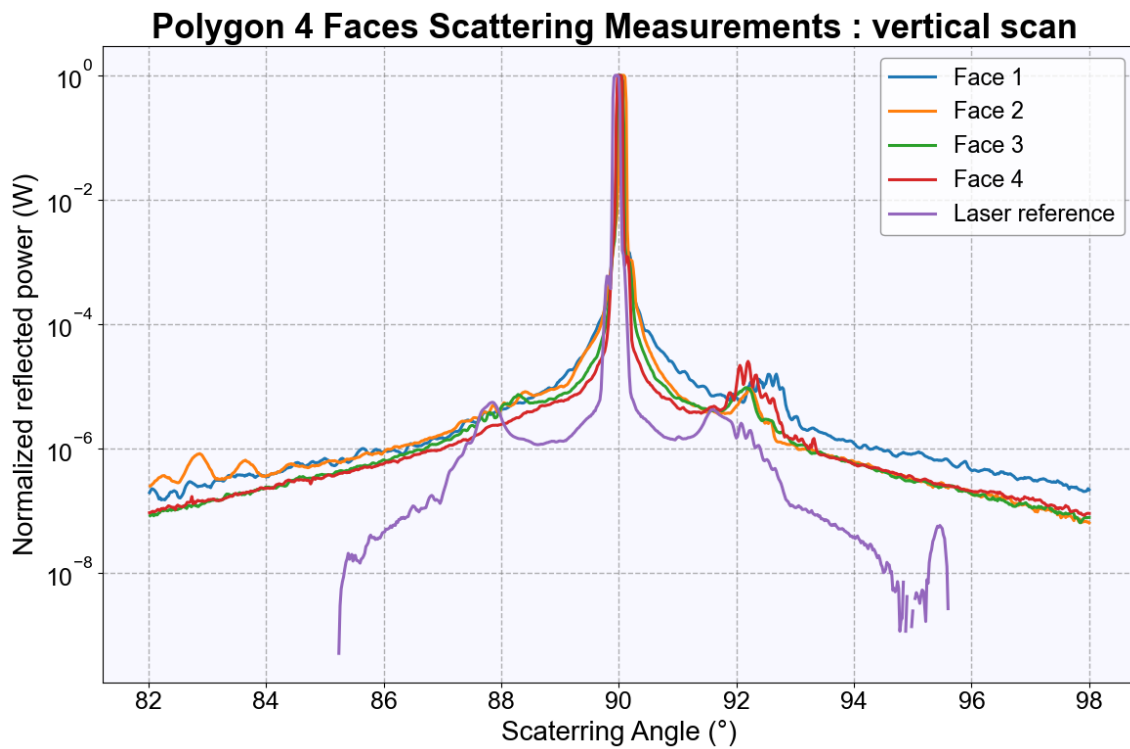


FIGURE 5.17: Scattering measurements of polygon in vertical and horizontal for the different faces

For the horizontal position, the results obtained for each face, see figure 5.18. Contrary to the results obtained for the vertical orientation, the results obtained for the horizontal orientation are quite distinct, as periodic peaks in the sample are evident, which could be

a result of the applied coating. These periodic peaks were only visible and well-defined for a portion of the angles, a conclusion that can be drawn from measurements taken with the polygon oriented in different ways. This inconsistency in peaks was observed both for positive angles (see Fig. 5.18) and for negative angles. This divergence may be attributed to the possibility that the coating applied to the sample was not uniformly distributed.

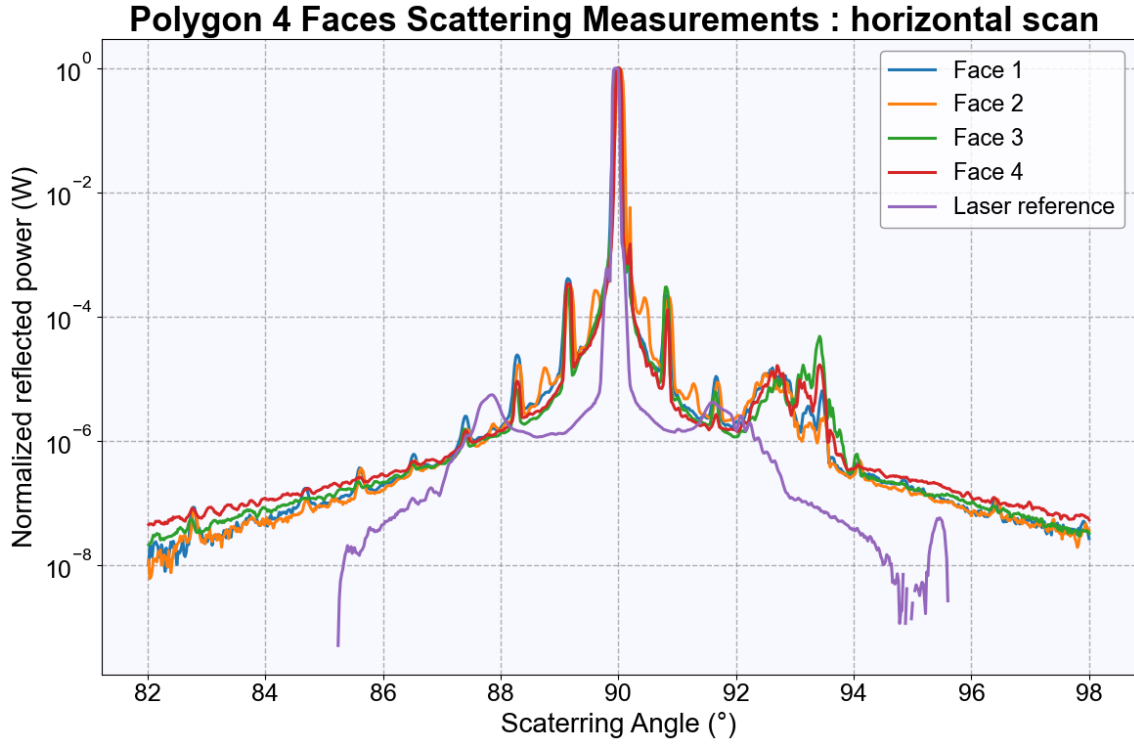


FIGURE 5.18: Scattering measurements of polygon in horizontal and for the different faces

The peaks observed demonstrate a distinct and consistent behaviour because, as the detection angle increases, there is a corresponding decrease in the intensity of the peaks. It was also concluded that face 2 exhibits more peaks, and a bigger symmetry between the two sides is also observed. Thus, due to this, and also for being the face with a surface presenting more impurities, it was the one chosen for the remaining measurements with the other lenses and with the scattering setup @Bosch.

5.3 Final remarks

In this chapter, we have validated the experimental setup developed in chapter 4. The setups analysed with various lenses and setups to explain their performance characteristics and the resultant implications for the measurements conducted. Both setups, the Large

Area and the Scattering Setup @Bosch, were comparatively assessed to comprehend the distinct impacts they imparted on the measurement. The Large Area configuration, despite its sizeable setup-related challenges, demonstrated superior efficacy in producing cleaner scattering with less noise and a larger angular dynamic range, as well as allowing the periodic peaks within certain angular ranges to be observed with bigger quality.

A comparative analysis revealed coherence and pattern uniformity in the results obtained from different lenses, reinforcing the reliability of the conducted studies. However, the variations in the intensity of the periodic peaks among different lenses emphasised the necessity of a lens selection based on the specific requirements of each study. The large area setup demonstrated its dominance in terms of achieving maximum intensity value, as opposed to the scattering setup @Bosch, which only achieved half of the maximum intensity value. The study of the Lambertian target, despite the challenging conditions and increased noise levels inherent to the Large Area setup, provided invaluable insights that were instrumental in facilitating comparisons between the lenses and the setups.

The detailed studies on various lenses, particularly LA1979, underscored the importance of lens characteristics in obtaining accurate measurements. The ideal focal distance for LA1979 was also identified, supporting the precise and reliable outcomes in subsequent measurements. Contrastingly, the Scattering Setup exhibited increased noise levels in the scattering, and despite its more symmetrical angular scan, it manifested limitations in the scanning range, impacting the overall quality of the results obtained.

In conclusion, the Large Area setup achieved higher intensity values, while the Scattering Setup @Bosch, despite its symmetrical angular scan, achieved only half of the maximum intensity value and exhibited limitations in the angular scanning range. The insights gained from these comparisons are instrumental in guiding the selection of appropriate setups and lenses for future studies, ensuring the reliability and accuracy of the measurements obtained.

Chapter 6

Final Conclusions and Future Work

During this work, a large area setup was developed, enabling the conduction of scattering measurements under diversified conditions, and the study of the existing scattering setup was simultaneously done. The combination of simulations with experimental work had an important part in the characterization of the systems and enlightening the fundamental behaviour of the setup parameters. This clarified important aspects of lens and setup characteristics and their consequential impacts on measurement accuracy and reliability. The findings from these studies served as a guide for selecting the most suitable components and lenses to meet the specific requirements and limitations of the setups. A significant difference observed between the setups was the variance in beam width. The large area setup produces a collimated beam, contrasting with the nearly focused beam in the Bosch-developed scattering setup. The former enables the collection of multiple averaged points, providing a broader angular view of the sample, while the latter yields more accurate results for detailed measurements of specific sample features. Despite the inherent limitations and discrepancies between them, the combination of both setups can facilitate studies with enhanced precision and reliability. For a full understanding of the sample, the large-area configuration is opted because it allows for wider coverage of the angular range, we could get more information for higher angles, and we were able to get a more general characterisation of the sample. For the precise examination of specific sample features, the scattering setup @Bosch is considered the optimal choice, as it yields more detailed and refined results. However, if the sample features exceed the size of the beam, they cannot be resolved or distinguished effectively by the setup. To conclude, this work has not only contributed to the development and understanding of scattering setups but also laid the foundation for future research, suggesting the potential integration

of different configurations to combine the unique advantages of each.

In future work, we would be interested in:

- Explore the calibration of the setup using Lambertian targets to compute the Bidirectional Reflectance Distribution Function (BRDF). This was a parameter left undetermined in this study, limiting our analysis to comparative power intensity only. The study of BRDF could allow for more nuanced and detailed comparisons between samples, potentially uncovering subtler differences in scattering characteristics.
- Conduct additional measurements using the developed setup and characterize a wider range of samples, including those of diverse types;
- Study the effects of stray light both in simulations and experimentally, and try to identify their origins;
- Improve the implementation of the Large Area setup, in order to minimise its instability and to ensure that measurements can be carried out without interference from the surrounding environment, and with more stable mechanical support elements;

Appendix A

Scattering main equations

1. Maxwell's Equations

$$\begin{aligned}\nabla \cdot \mathbf{E} &= \frac{\rho}{\epsilon_0} \\ \nabla \cdot \mathbf{B} &= 0 \\ \nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\ \nabla \times \mathbf{B} &= \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}\end{aligned}\tag{A.1}$$

2. Wave Equation

$$\nabla^2 \mathbf{E} - \mu_0 \epsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2} = 0\tag{A.2}$$

3. Born Approximation

$$f(\mathbf{k}, \mathbf{k}') = -\frac{m}{\hbar^2(k^2 - k'^2)} \langle \mathbf{k}' | V | \mathbf{k} \rangle\tag{A.3}$$

4. Fresnel Equations

The following equations are based in the figure A.1.

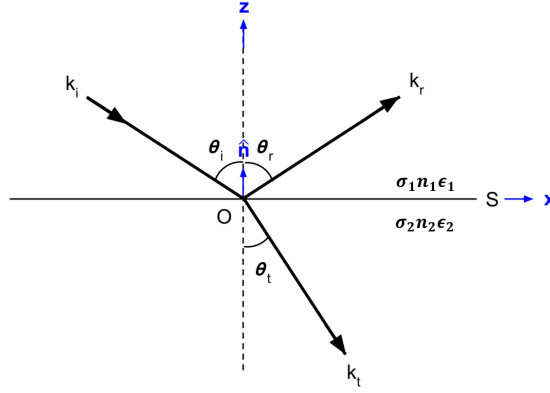


FIGURE A.1: Geometry for Snell's law.

$$\begin{aligned}
 r_{\text{parallel}} &= \frac{n_1 \cos(\theta_i) - n_2 \cos(\theta_t)}{n_1 \cos(\theta_i) + n_2 \cos(\theta_t)} \\
 r_{\text{perpendicular}} &= \frac{n_1 \cos(\theta_t) - n_2 \cos(\theta_i)}{n_1 \cos(\theta_t) + n_2 \cos(\theta_i)} \\
 t_{\text{parallel}} &= \frac{2n_1 \cos(\theta_i)}{n_1 \cos(\theta_i) + n_2 \cos(\theta_t)} \\
 t_{\text{perpendicular}} &= \frac{2n_1 \cos(\theta_i)}{n_1 \cos(\theta_t) + n_2 \cos(\theta_i)}
 \end{aligned} \tag{A.4}$$

Appendix B

Laser diode and simulation representation

For maximum coupling into single-mode fibers, an on-axis Gaussian beam with its waist at the fiber's end face and a waist diameter equal to the Mode Field Diameter (MFD) is advised. Traditional ray optics and Numerical Aperture (NA) are found inadequate for this application. The intensity profile (I) is better represented across the radial coordinate (ρ) by the mode distribution.

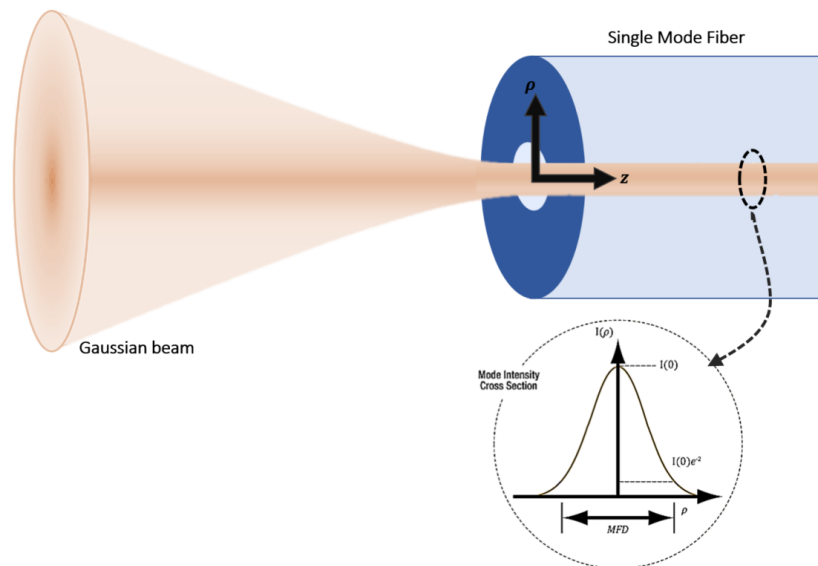


FIGURE B.1: Single Mode Fiber

Single-mode optical fibers, the specified Mode Field Diameter (MFD) is observed to enclose approximately 86% of the total beam power. This definition of spot size is often

deemed suitable for both collimating light from and focusing light into such fibers. When measured in the far field, a first approximation is commonly employed.[42]

The uncertainty of MFD was estimated here using the standard error of the mean.

Laser Source	
Wavelength (λ)	905 nm
MFD	$5.8 \pm 1.1 \mu\text{m}$
Numerical Aperture (Nominal)	0.10–0.14
θ_{SM}	$5.724 \pm 0.676^\circ$
Beam Size	$2.90 \pm 0.55 \mu\text{m}$
Position (s_0)	$0.0289 \pm 0.0619 \text{ mm}$

TABLE B.1: Source Gaussian parameters considered.

$$\theta_{\text{SM}} = \frac{\lambda}{\pi(MFD/2)} \approx \frac{0.64 * \lambda}{MFD} \quad (\text{B.1})$$

In this equation, the divergence or acceptance angle θ_{SM} is expressed in radians. Half the full angular extent of the beam is represented by this angle. The wavelength dependency is denoted by λ , and the beam's waist diameter is assumed to be equal to the Mode Field Diameter (MFD) of the fiber.

$$s_0 = \frac{MFD/2}{\tan(\theta_{\text{SM}})} \quad (\text{B.2})$$

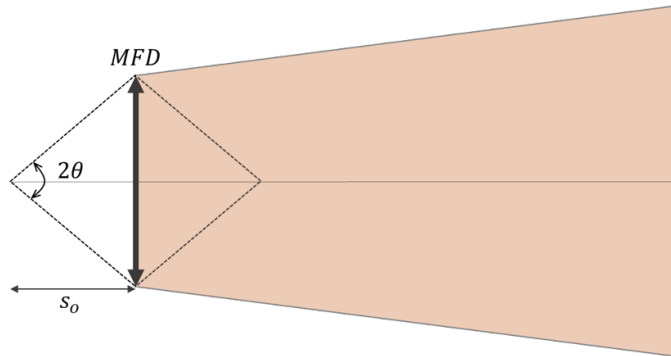
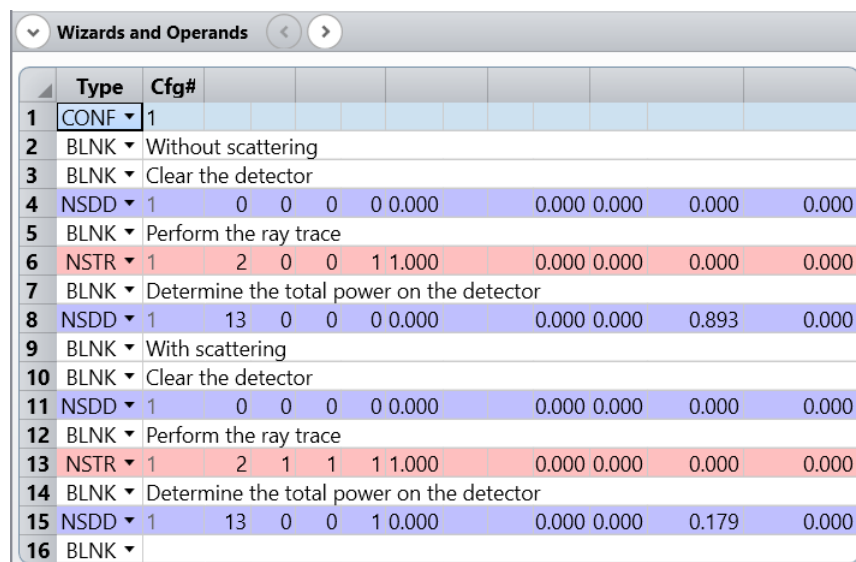


FIGURE B.2: Representation of the method used to calculate Beam Size and Position Zemax parameters of the SM fiber.

Appendix C

OpticStudio functions

During this thesis, the Merit Function was widely used from OpticStudio to make the simulation measurements. Below the merit function is specified.



	Type	Cfg#												
1	CONF	1												
2	BLNK		Without scattering											
3	BLNK		Clear the detector											
4	NSDD	1	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	BLNK		Perform the ray trace											
6	NSTR	1	2	0	0	1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7	BLNK		Determine the total power on the detector											
8	NSDD	1	13	0	0	0	0.000	0.000	0.000	0.893	0.000	0.000	0.000	0.000
9	BLNK		With scattering											
10	BLNK		Clear the detector											
11	NSDD	1	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12	BLNK		Perform the ray trace											
13	NSTR	1	2	1	1	1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
14	BLNK		Determine the total power on the detector											
15	NSDD	1	13	0	0	1	0.000	0.000	0.000	0.179	0.000	0.000	0.000	0.000
16	BLNK													

FIGURE C.1: Merit Function

To achieve the result, to choose the lens with the ideal characteristics, to then implement in the new setup, was created a ZPL (Zemax Programming Language). The code created is shown below.

```

1 # Defining parameter
2 G = NPAR(1,8,1)
3 E=NPAR(1,10,3)
4
5 E_min=0
6 E_max=0.8
7

```

```
8 E_range = E_max - E_min
9
10 samples=5
11
12 Step= E_range/(samples-1)
13
14 sample_d2=5
15
16 d2_min=20
17 d2_max=300
18 d2_step=(d2_max-d2_min)/sample_d2
19
20 DECLARE E, DOUBLE, 2,samples ,sample_d2
21
22 DECLARE flux, DOUBLE, 2, samples ,sample_d2
23
24 DECLARE d2, DOUBLE, 2, samples ,sample_d2
25
26 Declare angle, DOUBLE, 2, samples, sample_d2
27
28
29 For j, 0, samples-1,1
30
31 angle1=-0.5+(j/samples)
32
33
34 For d21, 1,sample_d2,1
35
36
37 d22 = d2_min+(d21*d2_step)
38
39
40 # Update detector Z position
41
42 # Loop over the different E positions
43
44
45 #FOR E_step, 0, samples-1, 1
46
47     d2(j+1,d21)=d22
48
```

```

49     # Calculate new Z position
50
51     angle(j+1,d21) = angle1
52
53
54
55     alfa= (E/G)
56
57     d3=alfa*d22
58
59     # Update detector Z position
60     SETNSCPARAMETER 1, 8, 3, d22
61
62     SETNSCPOSITION 1, 10, 3, d3
63
64     SETNSCPOSITION 1, 6, 4, angle1
65
66     #SETNSCPARAMETER 1, 10, 3, E_min+(E_step+1)*step
67
68
69
70     # Clear detectors
71     clear = NSDD(1, 0, 0, 0)
72
73     # Raytrace
74     NSTR 1,2, 1, 1, 1, 1, 0, 0
75
76     # Total power
77     flux(j+1, d21) = NSDD(1, 12, 0, 2)
78
79     FORMAT .9
80
81
82     print d22," ", angle(j+1,d21)," ", flux(j+1,d21)
83     #PRINT "E= " , E(E_step+1,d21)
84     #PRINT "flux= " , flux(E_step+1,d21)
85
86
87
88     #Return(E(E_step+1)(-1))
89 NEXT

```

```
90
91 next
92
93
94 # Y-axis label
95 banner = "x - angulo, y - d2 (dist ncia focal)" # Plot Banner
96
97 # Plot
98 PLOT2D NEW
99 PLOT2D BANNER, banner # Place the banner on the plot
100 PLOT2D DATA, flux, samples, sample_d2 ,1, 0,
101 PLOT2D GO
102
103 SAVEDETECTOR 1, 12, (file path)
104
105 GETTEXTFILE (file path)
```

CODE LISTING C.1: ZPL macro

Appendix D

Utilization of 2D Gaussian integral in Laser Beam Sizing

Laser systems frequently exhibit 2D Gaussian beams, that allow for a precise modelling approach. This appendix delves into the derivation of the intensity of the beam that passes through the pinhole of aperture a .

Mathematical Foundation

The 2D Gaussian function is a basis in laser beam characterisation and is articulated mathematically as follows, for generic parameters:

$$I(x, y) = I_0 e^{-(x-\mu_x)^2/(2\sigma_x^2) - (y-\mu_y)^2/(2\sigma_y^2)}. \quad (\text{D.1})$$

When it passes through a pinhole of aperture a , the beam is clipped and the total intensity $I_T(a)$ of the non-clipped beam can be given by integrating the 2D Gaussian profile in the pinhole area. If we perform such integration for $\mu_x = \mu_y = 0$ and $\sigma_x = \sigma_y$

$$\begin{aligned}
I_T(a) &= \frac{1}{2\pi\sigma^2} \iint_{\text{pinhole}} dx dy e^{-\frac{(x^2+y^2)}{2\sigma^2}} = \\
&= \frac{1}{2\pi\sigma^2} \int_0^a dR R e^{-\frac{R^2}{2\sigma^2}} \int_0^{2\pi} d\theta \\
&= \frac{1}{\sigma^2} \int_0^a dR R e^{-\frac{R^2}{2\sigma^2}} \\
&= \int_0^{\frac{a^2}{2\sigma^2}} e^{-u} du \\
&= \left[-e^{-u} \right]_0^{\frac{a^2}{2\sigma^2}} \\
&= 1 - e^{-\frac{a^2}{2\sigma^2}}
\end{aligned}
\quad \left\{ \begin{array}{l} V \cdot C. \\ u = \frac{R^2}{2\sigma^2} \\ du = \frac{R}{\sigma^2} dR \end{array} \right.$$

In this equation, the parameter a , represents the pinhole radius.

Integration of the 2D Gaussian function across the pinhole allows the deduction of the fit function, that has only one free parameter, σ . Such insight is invaluable to lasers study, as it offers an improved understanding of laser beam spatial distribution and propagation, ensuring greater accuracy in both sizing and application of laser beams.

Computation of Beam Dimensions Based on Intensity at e^{-2}

Another commonly used metric for characterizing the width of a Gaussian laser beam, or other distributions, is the Full Width at Half Maximum (FWHM). In the case of a Gaussian distribution, FWHM is related to the standard deviation (σ).

The intensity of a Gaussian beam is given by:

$$I = I_0 e^{-r^2/2\sigma^2} \quad (\text{D.3})$$

where σ is the standard deviation, w is the half width of the beam to the $1/e^2$ intensity point and r is the radial distance from the centre of the beam. The main condition for finding the FWHM is that the intensity falls to half of the maximum intensity:

$$\frac{I}{I_0} = 0.5 \quad (\text{D.4})$$

Solving this equation in terms of FWHM/2, full width of the beam at half of the maximum intensity divided by two, replaced r , the radial size. The following equation is obtained:

$$\frac{1}{2} = \exp\left(-\frac{(FWHM/2)^2}{2\sigma^2}\right) \quad (D.5)$$

$$\ln\left(\frac{1}{2}\right) = -\frac{1}{2} \frac{FWHM^2}{2\sigma^2} \quad (D.6)$$

$$FWHM = 2\sqrt{2\ln 2} \sigma \quad (D.7)$$

When solving for w , the correlation between (σ) at the $(1/e^2)$ intensity point is given by:

$$\frac{I}{I_0} = \frac{1}{e^2} \quad (D.8)$$

The r , the radial size, is replaced by w , $1/e^2$ width. The following equation is obtained:

$$e^{-2} = \exp\left(-\frac{w^2}{2\sigma^2}\right) \quad (D.9)$$

$$\ln(e^{-1}) = \left(-\frac{w^2}{2\sigma^2}\right) \quad (D.10)$$

$$-2\sigma^2 = -w^2 \quad (D.11)$$

$$w = \sqrt{2}\sigma \quad (D.12)$$

For conversions between FWHM and the beam diameter at the e^{-2} level, the following relations can be used:

$$FWHM = 2\sqrt{2\ln 2} \sigma \approx 2.3548 \sigma \quad (D.13)$$

$$w = \sqrt{2}\sigma \quad (D.14)$$

$$FWHM \approx \frac{2.3548}{\sqrt{2}} w \approx 1.6651 w \quad (D.15)$$

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