Msc Thesis
Development of snap-shot flexible chemiluminescence hyper-spectral imagery for combustion diagnostics

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MSC THESIS

DEVELOPMENT OF SNAP-SHOT FLEXIBLE CHEMILUMINESCENCE HYPER-SPECTRAL IMAGERY FOR COMBUSTION DIAGNOSTICS

by

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This thesis is confidential and cannot be made public until April 31, 2019.

An electronic version of this thesis is available at http://repository.tudelft.nl/.
The emission of green-house gases, such as carbon-dioxide, has been increasing rapidly in the last 50 years. Leading to an increase in the overall temperature, melting polar ice, rising sea-levels and more natural disasters. Aviation is one of the causes of these emissions. The efficiency of aircraft engines can be improved by improving the combustion. In order to optimise the combustion and the reduction of unwanted species in the emission, it is important to be able to predict how the flame will behave.

This thesis investigates snap-shot photography of multiple transient species in flames by recording chemiluminescence spectral information from a planar field obtained in a non-scanning procedure. Chemiluminescence is a process in which an electron gets into excited state by the chemical reaction and relaxes. When the electron relaxes, a photon is released with a wavelength characteristic for that species. Although information at one plane is desired, emissions from other planes will also be captured. The reason is because chemiluminescence is a passive technique where the signal corresponding to a pixel on the sensor is an integrated value of all planes in the line of sight of the pixel.

A survey was done on existing spectral imaging techniques. The existing techniques did not capture all the dimensions at once because they employed spatial scanning or band pass filters. The objective of this thesis was to be able to record all the spatial and spectral information simultaneously.

Two different setups were considered in this thesis, one to study the larger structures and one to study the details in the spectrum. The investigated setups consisted of a collecting lens, a transmission grating, a focusing lens system and an imaging sensor. Two gratings with different lines per mm were investigated, 1200 lines/mm (low spectral resolution) and 3039 lines/mm (high spectral resolution) respectively. Additionally, a spectrometer has been added to the setup to calibrate the captured image afterwards.

The flame used for this research was a hydrocarbon flame fed by a butane (80%) and propane (20%) fuel mixture. The chemiluminescence signal of this flame was weak, resulting in an integration time for the spectrometer of 8 seconds. The camera was more sensitive, but still required an exposure time of 0.5 seconds.

The point spread function at full width half maximum of the low resolution grating on the image sensor was determined to be 25.8\(\mu\)m. Using the magnification of the lens system, the smallest structure that can be observed in the flame can be computed. The smallest structure in the flame using the low resolution setup is 0.5mm. The high resolution grating had a point spread function at full width half maximum of 187\(\mu\)m, corresponding to a structure of 1mm in the flame.

For each of the results obtained, the corresponding spectrum by the spectrometer was used to calibrate the image. The spectrometer output was validated with spectra found in literature. The spectrum did not match the image for the longer wavelengths due to the non-linear dispersion of the grating. The spectral resolution of both setups was determined by using the shorter wavelengths. This is a conservative approach which will result in the lowest resolution. The spectral resolution of the low resolution grating setup was 0.15nm/pixel and 0.02nm/pixel for the high resolution grating setup.

With the low resolution grating setup attempts have been made to modify the flame to be a two-dimensional flame, this was to counter the effects of this line-of-sight technique. Of these attempts the V-flame was the most successful, it was practically two-dimensional and the larger structures in the spectrum were all separated. These frames have been used to construct a three-dimensional hyper-spectral data cube, which contains information of the spectrum for every two dimensional point. This is the main result of this thesis.

Although the results could be improved in many ways it can be concluded that the snapshot flexible chemiluminescence hyper-spectral imager is a useful addition to the existing species detection techniques. This thesis proved the working principles of this technique and further research is needed to extend the limits of this technique.
This thesis has been written as final deliverable for my Masters thesis and marks the end of my student career at the Aerospace Engineering faculty of the Delft University of Technology. A challenging journey of five and a half years has come to an end with the completion of this thesis, an investigation into the hyper-spectral imager for flame-front studies.

I would like to take this opportunity to thank my supervisor Dr. ir. Alexis Bohlin for the excellent guidance during throughout whole duration of the thesis. I would also like to express my gratitude to my parents, who over the years have provided me with an environment to perform and excel.

Lastly, I want to thank Kar Chun for occasionally helping me out with the experiments, reminding me to take breaks every now and then and aiding me defeating the Aerospace gym.

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NOMENCLATURE

ABBREVIATIONS

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<tr>
<td>ATAG</td>
<td>Air Transport Action Group</td>
</tr>
<tr>
<td>LIF</td>
<td>Laser-Induced Fluorescence</td>
</tr>
<tr>
<td>NIST</td>
<td>National Institute of Standards and Technology</td>
</tr>
<tr>
<td>PSF</td>
<td>Point Spread Function</td>
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<td>USAF</td>
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LATIN SYMBOLS

- $c$: Speed of light in vacuum
- $d_i$: Image distance
- $d_o$: Object distance
- $F$: Focal point
- $f$: Focal length
- $h$: Planck constant
- $I$: Image
- $m$: Diffraction order
- $M$: Magnification
- $n$: Index of refraction
- $O$: Object
- $R$: Radius

GREEK SYMBOLS

- $\lambda$: Wavelength
- $\theta$: Angle of a light-ray with a reference line
- $\theta_i$: Incidence angle of a light-ray
- $\theta_m$: Angle of diffraction of order $m$
The emission of green-house gases, such as carbon-dioxide ($CO_2$), has been increasing rapidly in the last 50 years. Leading to an increase in the overall temperature, melting polar ice, rising sea-levels and more natural disasters. Causes of the increase in these green-house gases are for example the industry, agriculture, electricity production and transportation. Aviation is part of transportation and accounts for 12% of the emissions in the transport category or 2% of the total emissions. [1]

Not only green-house gases are a concern, emissions of nitrogen oxides (NOx) and soot need to be reduced as well. Soot and NOx pose a health risk, as opposed to $CO_2$.

There is a general consensus that humans are the cause of these problems and that measures should be taken to reduce emissions. Using renewable energy sources, improving the efficiency of production processes and applying better isolation for houses are examples of measures being taken. The aviation industry, in the form of the Air Transport Action Group (ATAG), has set themselves goals to reduce emissions. One of the goals is to reduce the emission of carbon by half in 2050 compared to 2005.

In order to reduce the emission in aviation, aircraft need to be more fuel efficient. By reducing the total aircraft weight, the amount of fuel used will decrease; this can be achieved by using new lighter materials. Another way of improving the fuel efficiency is to decrease the aerodynamic drag. However, the biggest improvements have been achieved by better engines.

The efficiency of aircraft engines has been improved over the years by increasing the pressure ratio and also by increasing the by-pass ratio. In this thesis the focus will lie on the combustion chamber, to be precise, the flame. It is important to be able to predict how the flame will behave in order to optimise the combustion and the reduction of unwanted species in the emission. Of particular interest is the flame-front, which is the thin layer in which the chemical reaction takes place. The flame in the combustion chamber is of turbulent character [2], meaning that it is complex to model. Experiments are needed to validate and improve these models.

1.1. BACKGROUND

In this section an introduction is given on categories of measurement techniques, the principle behind chemiluminescence and how to use chemiluminescence to determine the flame-front.

1.1.1. CATEGORIES OF MEASUREMENT TECHNIQUES

Measurements can be taken at the location where the reaction is taking place, this can be done by putting a measurement device in the flow. This measurement technique is called in-situ. Another method is by taking samples of the reaction products with for example a filter and analysing them somewhere else. This technique is called an ex-situ technique.
The example mentioned for the in-situ technique was by putting a measurement device on the location. This method can be categorised as intrusive, as the reaction is being influenced by the measurement. As opposed to intrusive techniques, non-intrusive techniques do not interfere with the reaction.

The hyper-spectral imager that is developed for this thesis is categorised as in-situ and non-intrusive. The detection is using the properties of chemiluminescence, which will be discussed in more detail in the next section.

1.1.2. CHEMILUMINESCENCE IN A SIMPLE FLAME

Consider a laminar premixed Bunsen burner flame with methane as fuel. In Fig.1.1 a simplified representation of a flame-front in a premixed flame is shown. For the current case, the fuel would be methane and the oxidizer oxygen. The oxygen comes from the ambient air. In order to simplify reactions the inert gas N$_2$ will not be considered in the discussion. The reaction products would consist of carbon-dioxide and water, if a complete combustion is taking place. The chemical reaction equation is given by:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

(1.1)

![Figure 1.1: Simplified representation of the flame-front in a premixed flame. The flame-front is represented as a vertical wavy line. The flow is going from left to right with the oxidizer and fuel on the left of the flame-front and the reaction products on the right.](image)

The chemical reaction as shown in Eq.(1.1) is the global equation. The equation only takes into account what will be left after all reaction processes have taken place. In reality, lots of transient reactions take place, creating transient species. Some of these species have electrons that are excited due to the chemical reaction. In excited state the electrons have a higher orbit corresponding to a higher energy level. When the excited electron fall back to its original orbit, a photon will be emitted. The frequency of the photon is determined by the energy difference of the two orbits. The equation relating the energy difference and the emitted wavelength is shown in the equation below:

$$\lambda = \frac{hc}{\Delta E}$$

(1.2)

where $h$ is the Planck constant, $c$ the speed of light, $\lambda$ the wavelength and $\Delta E$ the difference in energy. Light produced by these chemical excited molecules is called chemiluminescence.

![Figure 1.2: Graphical representation of two electron orbits around an arbitrary atom. The difference in energy between two neighbouring orbits is denoted by $\Delta E$. An electron going from a higher energy orbit to a lower energy orbit emits a photon corresponding to the energy difference of the two orbits.](image)
A few of the reactions that produce chemiluminescence in a hydrocarbon flame are shown below, from Zhang et al. [3]:

\[
\begin{align*}
C_2 + OH & \rightarrow CO + CH^* \\
C_2H + O & \rightarrow CO + CH^* \\
C_2H + O_2 & \rightarrow CO_2 + CH^* \\
CH_2 + C & \rightarrow C_2^* + H_2
\end{align*}
\]

(1.3)

where the asterisk indicate that that molecule has an excited electron.

1.1.3. **Using chemiluminescence to locate the flame-front**

The excited electrons of the transient molecules will return to their original orbit in a relatively short time after they are formed, in the order of \(10^{-9}\) to \(10^{-7}\) seconds [4]. A typical laminar flame speed is around 1 meter per second, as can be concluded from the results of Yu et al. [5]. This means that the molecule would have moved roughly \(10^{-8}\) meters away from the point it was formed. Further away from the flame-front the molecule \(OH\) for example might still be present but is not emitting any photons any more and thus can not be detected passively. Other active techniques, where a laser beam is used to excite the electrons of a specific molecule, can be used to detect all molecules of that specie. However, molecules further away from the flame-front will also be detected. A comparison between passive flame-front measurement using chemiluminescence and active flame-front measurement using Laser-Induced Fluorescence (LIF) is shown in Fig.1.3, the figure was made by DANTEC Dynamics [6].

![Figure 1.3: The intensity of light emitted by the molecule OH for different radial locations from the burner nozzle. In this figure two techniques are compared, the technique making use of chemiluminescence and the Laser-Induced Fluorescence technique. [6]](image)

As can be seen from the figure, the LIF technique performs better in between the 2 flame-fronts while the chemiluminescence technique performs better outside the flame-fronts. The LIF technique illuminates one plane and only that plane will emit a signal. In the centre of the flame, the OH molecule has not been formed yet. The chemiluminescence technique is a line-of-sight technique, this means that not one plane can be isolated, but the whole scene will be captured. As the flame is three-dimensional, the flame-front corresponding to other planes will be captured as well. The light that reaches the sensor will be the result of an integration along a line. The integration along the edges of the flame will result in a higher intensity. The effects of a line-of-sight technique are illustrated in Fig.1.4.
Introduction

Sensor Pixel1 2
Desired object plane

Figure 1.4: Effect of line-of-sight on the image. The figure shows a top-view of a flame. The equally spaced circles represent the flame-front. It is assumed that each circle has equal intensity. Two exaggerated lines are shown indicating what a single pixel is viewing. One at the edge (1) and one in the centre (2). Pixel 1 will measure a higher intensity, as more circles are captured. Another effect of a line-of-sight technique is that other planes than the desired object plane will be imaged as well.

For the active species detection an expensive laser would be needed. So the investigation in a technique that does not rely on a laser would also be beneficial for the costs.

1.2. Research Question and Objectives

The goal of this thesis is to develop a hyper-spectral imaging device to study flame-fronts and flame species. The result will be a hyper-spectral data cube that contains species information for all points in the captured two-dimensional plane. The hyper-spectral imager will be built and tested using a Bunsen burner flame. The research objective is formulated as follows:

The research objective is to develop snap-shot photography of multiple transient species in flames by recording chemiluminescence spectral information from a planar field obtained in a non-scanning procedure.

The research question is formulated as:

How does the investigated design of the snap-shot flexible hyper-spectral imager perform in terms of temporal-, spatial- and spectral resolution?

1.3. Report Outline

This report will first review the basic working principles of optics in Chapter 2. The chapter will study the optics both theoretically and experimentally. After having obtained a deeper understanding of the optics, Chapter 3 will introduce existing spectral imaging devices, what their working principles are and how the hyper-spectral imager proposed in this thesis adds to the existing techniques. Chapter 4 presents the experimental setups and also elaborates on the design decisions made. The results obtained by these setups are analysed and discussed in Chapter 5. Finally Chapter 6 concludes this report and recommendations for future research are presented. In Appendix A all used equipment for both the investigation into optics and the finals setups are listed.
This chapter will discuss the basic principles and theories of optical devices such as lenses and gratings. Apart from the theoretical content, also a few basic setups that were experimented with will be discussed briefly. These will form the tools for the next phase, which is designing and building the actual hyper-spectral imaging device.

In literature it is conventional to describe light using geometric light rays and wave-fronts. In the geometric ray approach, the trajectory of photons are drawn. In the wave-front approach the light is considered as waves for which the wave-fronts are drawn. In Fig.2.1 an illustration is provided for both the geometric light ray approach and the wave-approach. In this report both representations are used, the choice of representation method depends on how well it can support the explanation in text.

Figure 2.1: The different conventions used to represent light in this report is presented in this figure. The figure shows light emitting from a point-source (a) using geometric light rays and (b) using wave-fronts.

2.1. BASIC THEORY ON LENSES

It is not always possible to place the measuring devices close to the spot where the chemistry is occurring. So the image has to be relayed to another location where it is convenient to take measurements. Another possibility is that the image is too small and thus cannot be discerned correctly by the measuring apparatus or too large to be fit on the imaging sensor. To solve this, the image needs to be enlarged or reduced in size. This section will discuss the investigation into the basic working principles of lenses, the relay of an image and the magnification of an image.

2.1.1. THE WORKING PRINCIPLE OF A LENS

The working principle of a lens is based on the refraction of light. Refraction occurs when light passes through materials having different indexes of refraction. When light passes through an optically denser material, the speed of light in that material decreases. The portion of the light that has not gone through the boundary of the denser material will have travelled a longer distance. This is represented in Fig.2.2 using plane waves.
The light rays are drawn perpendicular to the waves, these rays indicate the propagation direction of the light.

Figure 2.2: Light going from a optically less dense material \((n_1)\) to a material that is optically denser \((n_2)\), represented using a geometrical light ray and wave-fronts. The wave-fronts shown in the figure can be considered to be one wave-front at different instances in time, where the difference in time is kept constant.

The degree of refraction depends on the incidence angle of the light with the normal of the border between the two materials and the index of refractions of the two materials. Not all the light will be refracted, a portion of it gets reflected off the surface with an angle equal to the incidence angle. When the light ray hits the border perpendicularly, no refraction will take place. The refraction of a light ray can be computed using Snell’s law \([7]\):

\[
n_1 \sin \theta_1 = n_2 \sin \theta_2
\]  

(2.1)

where \(n_1\) and \(n_2\) are the indexes of refraction of the materials and \(\theta_1\) and \(\theta_2\) the incidence angle and refracted angle respectively. From this equation it can be seen that when \(n_1\) is smaller than \(n_2\) the light ray will be refracted towards the normal, when \(n_1\) is larger than \(n_2\) the light ray will be refracted away from the normal.

If the incidence angle is \(0^\circ\), which means that the ray is perpendicular to the border, no refraction occurs. This is summarised in Fig.2.3.

A lens has two of such borders that refract light. For a positive lens, parallel incoming rays will be focused on a single point, the focal point \((F)\), this is shown in Fig.2.4. The location of the focal point depends on the radii of curvature of the two lens surfaces. The distance from the focal point to the lens is defined by the focal length \((f)\).

The relation between \(f\) and the radii of curvature is represented by the lensmakers’ equation \([8]\):
2.1. **Basic Theory on Lenses**

**Figure 2.4: A lens having surfaces with radii of curvature** \( R_1 \) and \( R_2 \) **focusing parallel incoming light-rays on the focal point** \( F \).

\[
\frac{1}{f} = (n_{\text{lens}} - 1) \left( \frac{1}{R_1} - \frac{1}{R_2} + \frac{d(n_{\text{lens}} - 1)}{nR_1R_2} \right) \tag{2.2}
\]

where \( f \) represents the focal length, \( n_{\text{lens}} \) the index of refraction of the lens, \( R_1 \) and \( R_2 \) the radii of curvature for the two lens surfaces and \( d \) the thickness of the lens measured on the optical axis. The assumption made in this equation is that the medium surrounding the lens is air. The focal length of a lens is defined by the distance from a point on or inside the lens to the focal points on both sides of the lens. For a lens that has equal radii of curvature, the focal length would be measured from the centre of the lens. However, when the two surfaces have a different curvature, the point inside the lens might not be located in the centre. The point is located equidistant from both focal points.

For lenses which have at least one of the radii of curvature much larger than the thickness of the lens, \( d \ll R_1R_2 \), Eq.(2.2) can be rewritten as:

\[
\frac{1}{f} = (n_{\text{lens}} - 1) \left( \frac{1}{R_1} - \frac{1}{R_2} \right) \tag{2.3}
\]

In case of a plano-convex lens, one surface is flat. This flat surface has a radius of curvature of infinity. Then the lensmakers’ equation simplifies to:

\[
\frac{1}{f} = \frac{n_{\text{lens}} - 1}{R_1} \tag{2.4}
\]

**2.1.2. Thin-Lens Approximation**

For the thin-lens approximation the object distance (\( d_o \)), image distance (\( d_i \)) and lens focal length (\( f \)) are related through the lens formula in the following way [7]:

\[
\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \tag{2.5}
\]

The distances as described in the equation are graphically shown in Fig.2.5 with a positive lens which is assumed to be infinitely thin.
The magnification \( M \) equals the image height divided by the object height, because for both a triangle with equal angles can be constructed the ratio between the image distance and the object distance also equals the magnification. As the image becomes upside-down an extra minus sign is introduced. The equation for the magnification is:

\[
M = -\frac{d_i}{d_o}
\]

(2.6)

A real lens cannot be considered infinitely thin, but there is a way to still represent the lens as an infinitely thin-lens. In a real thick lens, there are two planes that can be defined to represent the thin-lens. There is one plane present for rays going left to right and one plane for rays that go the opposite direction. These planes are called the principal planes. The location of the principal plane can be determined by intersecting the incoming light ray and the outgoing light ray. This process is shown in Fig.2.6 for one principle plane.

Figure 2.6: The principal plane for light rays going from left to right represented as a black vertical thick line. The procedure to determine principal plane is by intersecting the ingoing and outgoing light-rays, as indicated with the dotted lines.

2.1.3. IMAGE RELAYING AND MAGNIFICATION

This section will discuss the magnification and relaying of objects using one or two lenses. The objects used are a divergent light-source and a collimated light-source (laser-light). The divergent light-source however, will be represented by an arrow of finite size instead of a point source. This is because the size of a point source is zero, which means that the magnification will not be clear. All the results in this section are computed using the lens formula in Eq.(2.5). The purpose of this chapter is to highlight some cases to give an intuitive understanding of what a lens does, and ultimately to be able to predict immediately without looking at the formula where the image will be located, whether the image is magnified or demagnified and which way to move a lens when attempting to collimate a light-source.
In this section the single lens, also referred as a 2f system, will be discussed for both light-sources. When the lens formula, as shown in Eq.(2.5), is used for varying object distances \(d_o\), the corresponding image distance \(d_i\) can be computed. With the image distance and object distance the magnification can be computed using Eq.(2.6). In Fig. 2.7 the result for a 100 mm focal length lens is shown. As can be seen the absolute size of the image for an object at twice the focal length (200 mm) is exactly 1. Furthermore when the object is between the focal point and the lens then the image is imaginary; when the object is on the other side of the focal point the image is real. For both cases moving the object further away from the focal point will decrease the magnification and moving closer to the focal point will increase the magnification. At the focal point there is a discontinuity where the magnification goes to infinity as well as the image distance. In the case of a light-source the light will be collimated when put at the focal point.

Figure 2.7: Magnification and image distance for different object distances with a single positive lens. The lens has a focal length of 100mm. An imaginary image is created when the object is closer than 1 focal length distance away from the lens. An imaginary image has a positive magnification. A real image is created for object distances larger than the focal length, the magnification is negative. Indicated with green is the special point at \(2f\), where the object distance equals the image distance and where the magnitude of the magnification is 1.

To get an even better feeling for the positive lens, the lens formula should not be considered. The lens should be considered as a device that bends and tries to converge the incoming light-rays. A lens is only able to bend light-rays to a certain extent. An object closer to the lens has rays that are incident on the lens under a greater angle than objects further away. When the object is too close to the lens, the lens is not able to bend the great incoming angle enough to let it leave as a converging bundle of light-rays, this happens when an object is between the focal point and the lens. If the object is exactly at the focal point, the lens can just bend the rays enough for them to leave the lens parallel to each other. When the object is further than one focal length away, the incoming divergent bundle of light-rays can be converted into a convergent bundle. While moving further away, the angle the ray is making with the lens is getting smaller and thus the lens is able to give the outgoing ray a stronger bend. This is summarised in Fig.2.8.

With this idea in mind it is easy to move the lens in the right direction when trying to collimate a light-source. If the outgoing light-bundle is converging, the lens should be moved closer to the light-source; when the outgoing light-bundle is diverging the lens should be moved away from the light-source.

For a perfect laser, the single lens configuration is rather straightforward. The light will be focused on the focal point on the other side of the lens. In reality lasers might not be perfectly collimated, then a lens can be
Figure 2.8: Geometric light rays for a light-source at different object distances. The green ray has an object distance less than the focal length, the light leaving the lens will be divergent. The red line depicts a light-source at the focal point, the rays leave the lens collimated. The black line represents the rays from a light-source that has an object distance larger than the focal length, the light will be converging after the lens. The blue line indicates a special point two focal length from the lens. The rays will be focused an equal distance behind the lens.

used to fix this issue.

**Two Lens System**

The simplest way to compute the location of an image utilizing a two lens system, is by considering one lens at a time. The image formed by a system of two lenses is computed by looking at the lens closest to the light-source first. This lens creates an image, which is used as object for the second lens. If the two lenses are sufficiently far apart so that their focal lengths are not overlapping, all images will be real. This is shown in Fig.2.9 for a divergent light-source. The case when two lenses are set sufficiently far apart that the focal-lengths do not overlap, then the laser-beam leaving the second lens will be converging. This is shown in Fig.2.10.

Figure 2.9: The first lens creates an image of the object, which acts as the object for the second lens. In the figure also the geometric light-rays used to construct the images are shown.

When the lenses are brought closer together so that the image created by the first lens is between the left focal point of the second lens and the second lens, the second lens will produce an imaginary image. The light rays after the second lens will be diverging, which can be seen by employing a collimated light-source. For a divergent light-source an imaginary image is created and can be seen when looking through the second lens. The case for the collimated light-source and the divergent light-source are presented in Fig.2.11.
2.1. Basic Theory on Lenses

Figure 2.10: The first lens focuses the collimated laser-beam on its focal point. This point then acts as a diverging point-source for the second lens. As this light-source has an object distance greater than the focal length, the laser-beam will be convergent after the second lens.

Figure 2.11: The first lens creates an image between the left focal point of the second lens and the second lens. This image is used by the second lens as object. Because this object is in-between the focal point and the second lens, the image created will be imaginary.
If the lenses are put even closer to each other such that the image formed by the first lens is on the right side of the second lens, the two lenses will act as a single effective lens. This is shown in Fig.2.12. The final image formed will be much closer to the lenses. The single effective lens will have a focal length that is shorter than both lenses. When two lenses with equal focal length are put on top of each other, the single effective lens will have a focal length that is exactly half of the focal length of the two lenses.

![Diagram](image1.png)

(a) Divergent light-source. The blue arrow on the right is the image of the first lens and the object for the second lens.

![Diagram](image2.png)

(b) Collimated light-source.

Figure 2.12: Two lenses put very close together such that the left focal point of the second lens is also on the left of the first lens. In this case the two lenses act as a single effective lens. This is demonstrated for a (a) divergent light-source and (b) a collimated light-source.

The last case that is considered has the focal points of both lenses on top of each other and having the object on the left focal point of the left lens. This is called a 4f-correlator. For a divergent light-source the first lens will collimate the light and the second lens will focus the light again. For the case of a divergent light-source the distance between the two lenses does not matter. In case of a collimated light-source, the first lens focuses the light on its focal point and the second lens collimates this light again as it is in its focal point. The magnification of the 4f system is defined by the ratio between the focal length of the second lens and the first lens:

\[ M = -\frac{f_2}{f_1} \]  

(2.7)

An example of such a 4f system for a divergent light-source and collimated light-source is shown in Fig.2.13.

A reason to use a 4f-correlator is for example to do Fourier-plane filtering, see Section 2.3. It can also be used for magnification or relaying an image. An argument to use two lenses for magnification is to reduce the spherical aberration when using plano-convex lenses, as one side is good for collimating and one side good for focusing, see Section 2.4.
2.1. **BASIC THEORY ON LENSES**

Figure 2.13: A 4f-correlator relaying an object. The magnification is defined by the ratio of the focal lengths of the two lenses. Figure (a) demonstrates the lens-system with a divergent light-source and figure (b) demonstrates the system with a collimated light-source.
2.2. **Basic Theory on Gratings**

In this section the principle behind a grating and the different types of gratings will be discussed.

### 2.2.1. The Principle Behind the Grating

Electromagnetic waves can be visible (visible light) or invisible (for example infra-red or ultra-violet) for the human eye. Electromagnetic waves can be seen as sinusoidal waves with a certain frequency, the frequency determines the colour of the light. The wavelength is often used to characterise electromagnetic waves instead of the frequency, the wavelength \( \lambda \) is defined as the speed of light in vacuum \( c \) divided by the frequency \( f \):

\[
\lambda = \frac{c}{f}
\]

Visible light is composed of waves with a wavelength ranging from 400nm (violet) to 750nm (red). Waves of shorter wavelengths contain more energy than waves of longer wavelengths. In Fig.2.14 the electromagnetic spectrum is shown [7].

![Electromagnetic Spectrum](image.png)

**Figure 2.14: Electromagnetic spectrum. [7]**

Electromagnetic waves can also bend due to refraction and diffraction. Refraction has been discussed in the previous section. Diffraction is defined as waves bending around an obstacle. This phenomenon can be explained using Huygens’ principle, which states:

*Every point on a wave front can be considered as a source of tiny wavelets that spread out in the forward direction at the speed of the wave itself. The new wavefront is the envelope of all the wavelets.*

This quote has been taken from ‘Physics for Scientists and Engineers with Modern Physics’ [7]. If a plane wave, a wave with all wavelets arranged on a plane or straight line in two dimensions, is passing through a plate with a slit, the wave front will not be planar any more. The wave front will be more circular, as the wavelets acts as a point source and emit in all directions. In two dimensions this creates a circular pattern and in three dimensions the pattern will be a sphere. Figure 2.15 shows this phenomena in two dimensions [7].
When more than one slit is present, the waves starting from the different slits will interfere with each other. Figure 2.16 shows the interference due to a double slit. The pattern shown depicts the intensity of the light.

Figure 2.16: A double-slit system produces a pattern on the screen. The pattern as shown qualitatively in this figure indicates the intensity of the light at that location. The letter \( d \) indicates the spacing between two slits, \( \lambda \) the wavelength of the light-source and \( \theta \) the angle between the slit and the other light-ray.

This pattern is due to the interference of the waves coming from the two slits. Because there is a difference in distance from each slit to a certain point on the screen, the waves might not be in phase. Due to interference the pattern on the screen can become brighter or not visible at all. When the pattern is bright, it is called constructive interference and when it is not visible, it is called destructive interference. When the path length from slit one to a certain point on the screen differs exactly 1 wavelength with respect to wave 2, the constructive interference is maximum. When the phase difference is half a wavelength destructive interference occurs and nothing will be visible. However, the wavelengths of both waves need to be identical. Constructive and destructive interference are graphically shown in Fig.2.17

Figure 2.16 shows the case with 2 slits, in this case there is a smooth transition between the peaks and the zeros. When more slits are added, the pattern will converge to the case where only the maximum constructive interference can be seen. Destructive interference will occur on all other locations on the screen. The principle of this is that at the point on the screen where maximum constructive interference occurs the path length is exactly the wavelength. At a point close to it, there are waves that are for example at 0.9 wavelengths and some at 1.1 wavelengths. These points on a sinusoidal wave have equal magnitude but opposite sign, so they will cancel. If the amount of slits is sufficient, the whole range in between wavelengths will be covered and destructively interfere.

To show the effect of adding more slits, a simple MATLAB program has been written. This program consists of points that represent the location of the slits and points that represent points on the screen. For each point on the screen the effect of all slit points are taken into account. This was done by computing the distance between the screen point and slit point and dividing it by the wavelength of the light. The decimal of the division will determine how much phase shift there is by multiplying it with \( 2\pi \). In this simulation the as-
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(a) Constructive interference

(b) Destructive interference

Figure 2.17: Graphical representation of constructive and destructive interference. This figure illustrates the addition of two waves (a) when they are in phase and (b) when their phases differ by half a wavelength.

Figure 2.18: Setup of the slit points and screen points of the slit simulation program. $s_1$ represents the screen point for which the influence of all slit points are computed, $L_i$ the length to the different slit points and $d$ the slit spacing.

A simulation has been done for a light source of 692 nm wavelength, a slit spacing of 1200 lines per mm and the screen positioned at a distance of 1 meter. The results for 2, 8, 16, 32, 64 and 128 slits are shown in Fig.2.19. From Fig.2.19f the location of the first order can be determined, which is 1.48 meters. This corresponds to an angle of about 56.03 degrees.

Constructive interference will not only occur at one wavelength difference, every integer multiple of one wavelength will also have constructive interference. When a monochromatic light source, light consisting of just one wavelength, is aimed on a system of multiple slits, the pattern that emerges on the screen will have multiple bright spots. The spot in the middle is the brightest, the zeroth order, the spots of higher order will lie further away from the middle and will be more dim. The locations of these spots depend on the wavelength. So when a broadband light source would be used, the individual colours will be shown on the screen on separate locations. For a white light source, a rainbow can be seen. This is summarised in the grating formula
2.2. Basic Theory on Gratings

\[ d \sin \theta = m \lambda \]  

(2.9)

Where \( d \) is the slit-spacing, \( \theta \) the angle to a point with constructive interference, \( \lambda \) the wavelength of the light and \( m \) is an integer number corresponding to the diffraction order. The first three variables were also shown in Fig.2.16. The simulation in MATLAB can be compared with the outcome when the grating formula is used with \( m \) set to 1.

\[
d \sin \theta = m \lambda \Rightarrow \theta = \sin^{-1} \left( \frac{\lambda}{d} \right) = \sin^{-1} \left( \frac{692 \cdot 10^{-9}}{1200 \cdot 10^{-3}} \right) = 56.14 \text{ deg}
\]

The value of 56.03 degrees is close to the value of 56.14 degrees. The more slits are added, the closer the value will approach the value computed by the grating formula.

2.2.2. Types of Gratings

In the previous section the simplest type of grating, the slit, was discussed. There are however more types of gratings each with their own advantages and disadvantages, which will be discussed in this chapter.

Manufacturing Processes

The first division in the kind of grating can be made in the manufacturing process. There are 2 ways of producing a grating, which is to create a repetitive pattern. The methods are ruling (ruled gratings) and photolithography using holography (holographic gratings) [9]. In the method of ruling a sharp tip is used to machine a pattern. In the photo-lithography method a photo-reactive layer is put on top of the base of the optic, then interference pattern is created with 2 lasers. The interference will create a periodic sinusoidal pattern on the photo-reactive coating. The advantage of the holographic grating is that in the process of producing the pattern no periodic errors, spacing errors and surface irregularities arise. This limits the stray light and ghosting. Ruled gratings have a higher efficiency than holographic gratings that have a sinusoidal pattern.
Reflective and Transmission Gratings

Another division made is whether the incoming light is on the same side as the diffracted light. A transmission grating has incoming light on one side and diffracted orders on the other side of the grating. The transmission grating often has an anti-reflective coating to maximise the amount of light going through the grating. The reflective grating has the light-source and the diffraction orders on the same side. As opposed to a transmission grating, the reflective grating is coated with a reflective layer to have as much light reflected as possible. The efficiency of both types are comparable. The transmission grating however, is in general less sensitive to aligning errors. Ruled transmission gratings can be both transmission gratings or reflective gratings, holographic gratings are of the reflective type.

In Fig.2.20 the transmission grating and reflective grating are shown. This image has been modified from the website of Thorlabs [10].

\[ d (\sin \theta_m - \sin \theta_i) = m \lambda \]  \hspace{1cm} (2.10)

and for the reflective grating by:

\[ d (\sin \theta_m + \sin \theta_i) = m \lambda \]  \hspace{1cm} (2.11)

where \( \theta_m \) indicates the angle of order \( m \) and \( \theta_i \) the angle of incidence.

The transmission grating is less angle sensitive than the reflective grating [11]. The higher-order diffraction follows the zeroth order diffraction. For a reflective grating, the zeroth order changes with incidence angle. For a transmission grating the zeroth order goes straight through the grating. This means that the zeroth order is not so much dependent on the incidence angle. As the higher orders go with the zeroth order, their angle will also not change. Figure 2.21 shows the effect of tilting a transmission grating and a reflective grating; this chart has been made by Ibsen Photonics [11].

Blazed Gratings and Littrow Condition

In order to increase the efficiency of the grating the grooves can be blazed. The grooves in a blazed grating are not just lines cut out, but have a saw-tooth pattern, as shown in Fig.2.22.

The angle \( \gamma \) is called the blaze angle. This angle can be tuned to give maximum efficiency for a certain wavelength for a certain order. The condition at which, for a certain wavelength and order, the diffraction is along the same line as the incoming light is called the Littrow condition. This condition maximises the efficiency.
2.2. Basic theory on gratings

Figure 2.21: Change in diffraction angle as function of the tilt of the grating. Results are plotted for the zeroth and first order of a reflective grating and transmission grating. [11]

Figure 2.22: Graphical representation of a blazed grating. \( d \) Represents the line spacing and \( \gamma \) the blaze angle.
2.3. **FOURIER PLANE SPATIAL FILTERING**

In this section the ability of lenses to perform a Fourier transform will be discussed. First some general information is given on the Fourier transform, then the Fourier transform in optical systems is discussed and finally the possible uses of filtering in the Fourier plane will be examined.

2.3.1. **THE FOURIER TRANSFORM**

The Fourier transform transforms a signal that is in the time domain to the frequency domain. All the frequencies embedded in the signal can be discerned after Fourier transforming. In the time domain a pure sinusoidal wave would have a repeating pattern, in the frequency domain the corresponding frequency will be shown as a Dirac function in the frequency plane, as shown in Fig.2.23. In the figure, the frequency spectrum has been normalised by the amount of sampling points and multiplied by two, in order to have the amplitude correspond to the amplitude of the sinusoidal wave.

![Figure 2.23: A sinusoidal signal of 50 Hz in the time domain and in the frequency domain. The frequency spectrum has been normalised with the amount of sampling points and multiplied by 2, as the negative portion has been neglected. In the ideal case the peak would be a Dirac function with the amplitude corresponding to the amplitude of the sinusoidal input wave.](image)

Multiple sinusoidal waves can be added together to form a new wave, this is shown in Fig.2.24. With the right combination of waves with the correct frequency and amplitude, signals that are not wave-like, such as pulses and ramps, can be approximated.

There exists also a Fourier transform in two dimensions. Instead of considering the sinusoidal waves as lines, the sinusoidal waves should be considered as wavy sheets in 2 dimensions. These waves now not only have a frequency and amplitude, but also a direction. This is depicted in Fig.2.25 in which the Fourier plane is shown using a Cartesian coordinate system. The horizontal axis represents the frequency in the vertical direction (Fv) and the horizontal axis represents the horizontal frequency (Fh). The waves shown in the figure are representations in the spatial domain. In the Fourier plane each of these depicted waves would be a point at the location in the coordinate system that corresponds to the frequencies of the wave.
2.3. FOU RIE R PLANE SPATIAL FILTERING

Figure 2.24: A wave can be built-up using sinusoidal waves with different amplitudes and frequencies. The red wave is built up by the sinusoidal waves in blue.

Figure 2.25: Fourier plane with on the horizontal axis the horizontal frequency \((F_h)\) and on the vertical axis the vertical frequency \((F_v)\). In the plane a few cases of waves with different horizontal and vertical frequencies are shown. The representation of these waves are in the spatial domain. In the frequency domain these waves would be a point in the plane with corresponding frequencies.
The low frequencies contribute to the overall shape of the signal or object, while the high frequencies contribute to the sharpness or the outline of the signal or object. When a filter is applied to only let low frequencies pass, an object will become blurred. If only the high frequencies are passed, only the edge will be visible.

In Fig.2.26 a square (two-dimensional shape) is transformed from the spatial domain to the frequency domain with a Fourier transform. The transformation is performed using the fft2 function in MATLAB. Then either a portion of the high frequency or low frequency in the Fourier plane is blocked. This new situation then is transformed back to the spatial domain using the inverse Fourier transform, the corresponding function in MATLAB is ifft2 function. As the square only consists of sides that are parallel with either the horizontal axis or the vertical axis, the bright points in the Fourier plane lie predominantly on the horizontal and vertical axes. In Fig.2.26a the high frequencies in the horizontal direction are blocked, the high frequencies in the vertical direction are allowed to pass. This means that there will not be enough high frequencies for the vertical sides of the square to be reconstructed sharply. In Fig.2.26b all the horizontal high frequencies are passed. The absence of the lower frequencies causes the overall shape to be absent as well, what remains are the two edges that are formed by the higher frequencies. The two horizontal edges are not visible, because the higher frequencies in the vertical direction are also blocked.

![Image of Fourier Transform](image)

**Figure 2.26:** An image of a square is transformed to the frequency domain using the Fourier transform. In (a) the high frequencies are blocked and in (b) the low frequencies are blocked. After the frequency filtering, the inverse Fourier transform is applied to recreate an image. These transformations have been performed in MATLAB.

### 2.3.2. Fourier Transform in Lenses

A positive lens is also capable of performing a Fourier transform. The Fourier plane of a lens system lies in the focal point of the lens. The Fourier transform can only be made visible when a collimated beam of light is blocked by a shape. To show this property of a positive lens an experiment has been done, the setup is shown in Fig.2.27.

The numbers in Fig.2.27 represent the following:

1. 692nm laser
2. Microscope objective with magnification 20
3. Pinhole for removing imperfections in the laser beam
2.3. **FOURIER PLANE SPATIAL FILTERING**

The laser is the light source. Because the laser beam is too small, a microscope objective is used to magnify the beam. This is done by focusing the laser beam with the microscope objective, a plano-convex lens is then used to recollimate the laser beam. The magnification is obtained by the difference in focal lengths of the objective and the plano-convex lens, this principle has been discussed previously. A pinhole is placed at the focal point of the microscope objective to remove imperfections in the laser beam. These imperfections are due to imperfections in the laser itself and also due to dust particles that were accumulated inside the microscope objective. The light that comes out of the laser is not circular shaped, but has a rather oval shape. To create a circular laser beam, an aperture is placed after the collimating plano-convex lens. This also limits the beam width, will be incident on the next lenses more in the centre. By passing through the lens in the centre will reduce the spherical aberration. Spherical aberration will be discussed in the next section. After the aperture, an USAF 1951 target is placed, which is used to imprint a known spatial patter in the beam. The used USAF target is shown in Fig.2.28 [12]. Next, a lens is placed one focal length distance away from the USAF target. The USAF target is placed in the focal point because then the shape will be collimated. The laser light is as if it is originating from infinity, but due to diffraction at the edges of the illuminated shape on the USAF target, the object is at the location of the USAF target. At the focal point on the other side of the lens a slit is placed that can block a portion of the laser beam. The slit is located at the Fourier plane and can thus be used as a spatial frequency filter. After filtering, another lens is used to collimate the laser beam and to focus the shapes on the aperture with a piece of paper on it.

Note that the rays of the object to the image does not have to coincide with the rays of the light source!

As shape, the largest square on the USAF target was chosen. Two filtering operations were performed, low-pass filtering and high-pass filtering. As the filter was a slit, the filtering was only performed in one direction, just as was done in the MATLAB case. However, for the high-pass filtering case it was not possible to only block the low frequencies with the slit. As a consequence one side of the high frequencies needed also to be blocked. The results are shown in Fig.2.29.

As can be seen in the figure, the original shape has sharp edges, see Fig.2.29a. When the low-pass filter has been applied the vertical edges become blurred, while the horizontal edges remain sharp, see Fig.2.29b. If the high frequencies on one side are passed, only the vertical edges can be seen, see Fig.2.29c. These experimental results coincide with the results obtained with MATLAB. One difference is that in the experimental results an additional ring is visible in the high-pass case. This ring originates from the aperture, as the aperture blocks part of the light and thus produces an edge.
Figure 2.28: USAF target used in the experiments, by Thorlabs [12]

Figure 2.29: Fourier plane filtering of a square.

(a) No filtering  (b) Low-pass filtering  (c) High-pass filtering
2.3.3. APPLICATIONS OF FOURIER PLANE FILTERING

As mentioned earlier, the Fourier plane filtering only works when an object is put in a collimated beam of light. The use cases for this is thus limited. One of the uses are for example to remove imperfections in the laser beam. The pinhole used in this experimental setup acted on the Fourier plane and removed all higher frequency components in the laser beam, the result of filtering can be seen in Fig. 2.30.

![Unfiltered laser beam](image1)
![Filtered laser beam](image2)

(a) Unfiltered laser beam.
(b) Filtered laser beam.

Figure 2.30: Removing imperfections in the laser beam by means of Fourier plane filtering. The pinhole employed for the filtering is a form of low-pass filtering.

Although for the current project there are not so many uses for the Fourier plane filtering, building one has increased the understanding of optics.

2.4. PRACTICAL CONSIDERATIONS WHEN WORKING WITH LENSES

In this section some of the practical considerations that were relevant for the setups used will be discussed, such as how to setup and align a lens system, optical aberrations and incorporating a measurement device such as a camera into the setup.

OPTICS ALIGNMENT

There are a few steps that can be followed to align a lens system. For the alignment a laser is used. This laser needs to be aligned itself first. The next steps describes how to perform both the laser alignment and lens alignment.

1. Setup an aperture with the desired height.
2. Setup the laser with multiple posts to allow for more degrees of freedom. The laser is attached to a horizontal post, which in turn is attached to a vertical post, see Fig. 2.31.
   (a) Put aperture from (1) in the near-field of the laser.
   (b) Align the height of the laser by translating the laser up or down only, see Fig. 2.32a.
   (c) Put aperture from (1) in the far-field.
   (d) Align the height with the aperture by only rotating the laser up or down, see Fig. 2.32b.
   (e) Iterate previous steps until desired accuracy has been reached.
   (f) Put a collar on the vertical post of the laser to fix the height.
3. Take a second aperture and calibrate the height using the laser.
4. Fix the 2 apertures on a breadboard. In case the desired direction of the laser is aligned along one of the sides of the breadboard, the breadboard can be used to make sure the apertures are aligned in a straight line.
5. Calibrate the horizontal alignment of the laser.
   (a) Point the laser on the closer aperture by translating left and right only, see Fig. 2.32c.
   (b) Point the laser on the farther aperture by rotating the laser left and right only, see Fig. 2.32d.
(c) Iterate previous steps until the desired accuracy has been reached.

6. Aligning the lenses.

(a) Put the lens on the desired location between the 2 apertures.

(b) The lens does reflect part of the light. This property can be used to aid in the alignment. By holding a screen (piece of paper) next to the opening of the aperture, it can be checked for where the reflection is. By rotating the lens and translating the lens up or down while looking at the reflection, the lens can be aligned. When no reflection can be observed, the lens is aligned. For higher accuracy the size of the aperture should be decreased.

Figure 2.31: Method of attaching the laser to a horizontal and vertical pole to allow for more degrees of freedom.

Figure 2.32: Adjustments made to align the laser

Spherical aberration

Spherical aberration is the inability of a spherical lens to focus collimated incoming light onto one single point in the axial direction. This is due to the spherical shape and the effect can be reduced by using different shapes of lenses. The lenses that are used in this thesis are of the plano-convex type, which has one flat surface and one spherical surface. The plano-convex lenses are good for focusing or collimating light. The orientation of the lens is important, as it determines the severity of the spherical aberration.

Spherical aberration is purely due to the shape of the lens. This can be shown using ray-tracing and Snell’s law. A MATLAB code was developed to allow for easy implementation of a lens that can be used for the ray-tracing.

Figure 2.33 shows a comparison between the spherical aberration of the same plano-convex lens, but oriented differently with respect to the incoming collimated light beam. As can be seen, the focus in Fig2.33b is better than in Fig2.33a when comparing the smallest bundle heights. It can also be noted that the rays closer to the edges of the lens are bent more in comparison with the rays near the optical axis, so the spherical
aberration is more pronounced near the edges. The focal point is defined as the point where the light ray are brought together. When there is spherical aberration there is no single point where all the rays intersect. So the focal point would be determined at the location where the rays are closest together. When seen in three dimensions, this location looks more like a circle. Thus it is called the circle of least confusion.

![Image](image1.png)

(a) The planar surface facing the incoming rays. The light-rays are incident from left to right.

![Image](image2.png)

(b) The spherical surface facing the incoming ray. The light-rays are incident from left to right.

Figure 2.33: Comparison between the orientation of a plano-convex lens with respect to a collimated incoming beam of light.

To demonstrate the effect of spherical aberration in practice, a small test has been performed. In this test a small bundle of collimated light is incident on the plano-convex lens at the outer region, this is done for the two orientations. The ray-tracing performed in MATLAB is depicted in Figure 2.34. The lens used has a focal length of 100 mm. As can be seen from the figure, the focal points are different.

The ray-tracing example in MATLAB was also performed using lenses. In this real experiment, an image plane was placed at a fixed location. First the spherical side was pointed towards the incoming light source. The lens was positioned such that it focused the light on the image plane. Then the lens was rotated to have the planar side facing the incoming light. When observing Fig.2.34, it is expected that when the distance to the image plane is unaltered, the image would look stretched. After rotating the lens, the lens is translated to have the best focus on the image plane. As the focus is worse in this orientation, it is expected that the dot on the image plane is larger. These results are shown in Fig.2.35.
Figure 2.34: Comparison between the orientation of a plano-convex lens with respect to a collimated incoming beam of light passing through the edge of the lens. The direction of the light-rays are from left to right.

Figure 2.35: Experimental investigation on spherical aberration by letting a collimated light bundle pass through the outer region of the lens. (a) Spherical surface facing the incoming light. (b) Planar surface facing the incoming light, by rotating lens without adjusting the image distance. (c) Planar surface facing the incoming light and with the lens repositioned to have the best focus.
2.4. PRACTICAL CONSIDERATIONS WHEN WORKING WITH LENSES

So from these experiments the spherical aberration in the used plano-convex lens is shown. With these results it can be concluded that the spherical surface should face the incoming light when a collimated lightsources needs to be focused and that the planar surface should face the light source when a diverging source needs to be collimated.

RESOLVING POWER OF AN OPTICAL SYSTEM

In an ideal situation a point light source imaged through a lens onto an image plane, would remain a point. However, in reality lens systems are not capable of perfectly imaging a point. The transition of going from complete darkness to the bright spot created by the light source is not instantaneous. There will be a gradual change in intensity. This gradual change is described in a Point Spread Function (PSF). In Fig.2.36a a qualitative representation of the point to be imaged is shown. The intensity of the point has a Gaussian distribution, shown in Fig.2.36b in 3 dimensions and shown in Fig.2.36c along the black line as drawn in Fig.2.36a. If the lens would be an ideal lens that could focus a point source onto a point, then the PSF would be zero everywhere except for one location, this is shown in Fig.2.36d. The maximum spatial resolution of a lens or lens-system is determined by how narrow the PSF is.

Figure 2.36: Qualitative representation of a Point Spread Function. The intensity indicated is the normalised intensity. (a) Point represented as normalised intensity. The black line indicates where the line-plot in Fig.2.36c is taken. (b) Three dimensional representation of the Points Spread Function of a non-ideal lens. (c) Point Spread Function for a non-ideal lens. (d) Point Spread Function for an ideal lens.
In this section two aspects of incorporating a camera in an optical system will be discussed: the lens of the camera and things to consider when taking an image. The camera used in this investigation is a Canon 100D with a 18-55mm IS STM lens.

The camera-lens
As stated on the camera lens, the lens-system should act as a single equivalent lens with a focal length of 18mm when fully zoomed out and 55mm when fully zoomed in. Since lenses on cameras have a focus-ring, which can be used to select which plane to focus on, the exact location of the camera is of less importance for the focus. To investigate whether the camera lens actually functions as a 18mm or 55mm equivalent lens, an experiment has been done. The experimental setup is shown in Fig.2.37. The set-up is very similar to the set-up in Fig.2.27.

![Figure 2.37: Setup with a camera. The red lines represent the laser beam and the black lines the imaging rays from the object to the image plane.](image)

The numbers in the figure indicate the following:

1. Canon 100D camera
2. Lens 100mm focal length
3. USAF 1951 test target (100 mm from the lens)
4. Iris
5. Lens 100mm focal length (used to collimate the laser light)
6. Pinhole
7. Microscope objective 20x magnification
8. 692nm laser

The object being illuminated on the USAF target is the largest square, as was shown in Fig.2.28. The square has dimensions of $9.1\text{mm} \times 9.1\text{mm}$. In the experiment, the camera lens is set to a focal length of 55mm. The magnification of the lens system (containing of the camera lens and the lens denoted by the number 2) is $\frac{55\text{mm}}{100\text{mm}} = 1:0.55$. So the expected size of the image on the camera sensor is: $\frac{55\text{mm}}{100\text{mm}} \cdot 9.1\text{mm} = 5\text{mm}$.

The sensor dimensions are $22.3\text{mm} \times 14.9\text{mm}$, as obtained from the official site of Canon [13]. By approximating the amount of pixels of the square in the image and the sensor size, the actual size of the image of the square on the sensor can be determined. The approximation of the amount of pixels is shown in Fig.2.38.

The amount of pixels in the horizontal direction is 1201 and the amount in vertical direction is 1196. The total amount of pixels in horizontal direction is 5184 and the amount of pixels in vertical direction is 3456. The actual width is 5.16mm and 5.16mm for the width and height respectively. As can be noticed there is a small difference in predicted size and the actual size. The difference might be explained due to the limit in how precise the alignment could be done, the approximation of the amount of pixels and the spatial resolution of the lens. But overall it can be concluded that the camera lens just functions as an equivalent single lens.
2.4. PRACTICAL CONSIDERATIONS WHEN WORKING WITH LENSES

Figure 2.38: A photograph taken of the image of the largest square on the USAF target. The lines in the figure are used to approximate the amount of pixels of the image of the square.

Taking an image
Consider Fig.2.39, which is a purely qualitative sketch. In the figure a light source is collimated by the collimating lens. This collimated light then passes through a transparent plate with shapes on it, the USAF target from Fig.2.28 has been used for this purpose. Another lens then creates an image of the illuminated shapes on the image plane. When a camera is placed behind the image plane and focuses on the image plane, one would expect to get the whole picture. As the image is not an actual object that diffuses light, the image of the shape can not be observed from all angles and locations. As can be seen from Fig.2.39, light rays might miss the lens of the camera. In fact, there is a big chance that a light ray will miss, because the size of lens opening is limited. A better approach is to collimate the rays from the object and use the camera for the focusing.

Figure 2.39: A divergent light-source is being collimated and passed through a transparent plate with shapes. These shapes imprint a pattern in the collimated beam of light. The transparent plate is also where the object plane is located. The object plane does not correspond with the focal point of the second focusing lens and creates an image at the image plane indicated in the figure. The camera is put sufficiently aft of the image plane to allow the camera lens-system to focus on this plane.

An important aspect to keep in mind is that lens systems of cameras can only focus from infinity to a certain distance near the camera. Often this near distance is about 250mm. For objects at infinity the light rays are collimated. For all objects closer than infinity, the light-rays are diverging. Therefore the camera is only able to focus collimated light and diverging light (to a certain extent).

If a positive lens is put in front of the camera lens while a collimated beam of light is incident on the camera, the light that enters the camera lens is converging. This type of light can not be focused with the camera lens. By placing the positive lens in front of the camera, the camera is effectively made near-sighted. The image will be formed in front of the camera sensor.
BACKGROUND ON HYPER-SPECTRAL IMAGING

In this chapter a brief background on spectral imaging methods are provided. This chapter will also discuss where the hyper-spectral imaging developed in this thesis fits in the existing spectral analyses methods. First an experimental setup will be discussed built to investigate and understand the convolution between frequency and space, as this is a potential problem. This experiment helped in understanding gratings and also helped in understanding the choices made in the spectral imaging techniques.

3.1. CONVOLUTION BETWEEN FREQUENCY AND SPACE

In this section the dispersion of a light source using gratings is studied in more detail. Problems as convolution between frequency and space will also be addressed.

The type of grating considered in this section will be a transmission grating that has grooves only in one direction. This means that the dispersion will be in one direction, this is illustrated Fig.3.1.

Figure 3.1: Transmission grating dispersing horizontally. The shorter wave-lengths have a smaller dispersion angle.
Consider a two-dimensional object that emits a spectrum, if this emitted spectrum is passed through the transmission grating, each point on the two-dimensional object will get dispersed equally. For each wavelength in the spectrum with non-zero amplitude, a point on the original object will create a point on the dispersed image. Because the diffraction angle of a single wavelength is the same for each point on the object, the dispersed image for a very narrow band object will have the exact same dimensions, as the original. To test this idea, the Fourier setup, as shown in Fig. 2.27, has been modified to incorporate a transmission grating. The modified setup is shown in Fig. 3.2.

The result of this experiment is shown in Fig. 3.3. In the picture it can be seen that the zeroth order and the first order have the same shape and size. It can be observed that the first order is dimmer, but is as crisp as the zeroth order. This might not be visible in the image, because the distance of both orders to the camera were different, and caused one of the images to be a bit sharper.

If the light source is not monochromatic but consists of two wavelengths, two images will be formed. Depending on the separation of the two wavelengths, the amount of grooves in the grating (more grooves means that the wavelengths will be further apart) and the size of the image/object there may appear two separate images, Fig. 3.4a. It could also be that the images are either too big, the wavelengths too close to each other or the dispersion of the grating not great enough, this will cause the overlap of the two dispersed images, as illustrated in Fig. 3.4b. When the object is a broadband light source, the original shape can not be recognised anymore, as shown in Fig. 3.4c.

In the two-dimensional case the frequency and the space were convoluted. The frequency information was entangled with the spatial information in 1 direction. When an one-dimensional feature is used in which the spatial information and the frequency information is on 2 separate axes, there will be no convolution between space and frequency. This principle is shown in Fig. 3.5.

To show this convolution between space and frequency experimentally in two dimensions without having an object that is capable of emitting light itself, is not trivial. So instead of a demonstration in two dimensions, a convolution example in one dimension was performed. Instead of dispersing the different wavelengths along
3.1. **CONVOLUTION BETWEEN FREQUENCY AND SPACE**

Figure 3.4: Dispersion of a two-dimensional object emitting multiple wavelengths. These figures illustrate the problem of overlapping dispersed images. This is referred to as the convolution between space and frequency.

Figure 3.5: Dispersion of a one dimensional object emitting a broadband spectrum.
an axis different from the axis on which the spatial feature is on, the dispersion will be performed on the same axis.

First of all a white light-source was dispersed using a transmission grating. Then this dispersed light was collimated in one direction with a cylindrical lens. The cylindrical lens was used to have the colours collimated but still retaining the bigger size for each colour. Then a slit was used to select a portion of the wavelengths. This band is then passed through an USAF target to imprint a pattern in the light, the shape that has been used was the largest square. This square splits the band into an upper half and a lower half. A spherical lens located one focal length away then collects the square on the USAF target, after which a transmission grating disperses it vertically. Vertically because then the frequency will lie on the same axis as the shape. Finally, a camera was positioned behind the grating to focus the image on the sensor. The whole setup is shown in Fig.3.6.

Two experiments were performed, one which did not had any shape blocking the band and one that had the square on the USAF target blocking the spectrum. First it is discussed how the optics act on the band and a simulated result will be shown. For the first case where nothing is blocking the collimated band entering the last spherical lens, the band at that location would look like Fig.3.7a. When the light passes the transmission grating that vertically disperses the different wavelengths, each wavelength will be dispersed under a different angle. This can be visualised as in Fig.3.7b, although the representation might not be what is happening physically it still gives a good understanding. This dispersed band will then be focused onto 1 line by the last lens. In this experiment this last lens was the camera lens. In the simulation this was done by summing all colour-values on one row and averaging, the result is shown in Fig.3.7c.

If a square is present that is blocking part of the collimated spectrum, the light immediately after the USAF target would look like Fig.3.8a. After a vertical dispersion by the transmission grating it would look like Fig.3.8b. Note that the dispersed representation might not represent the real physical situation but is solely used for understanding what is happening. Finally, all rows were summed and averaged to have the image that would appear on the sensor, as shown in Fig.3.8c. As can be seen, the image looks like two smaller versions of the image presented in Fig.3.7c. This is because the square is big enough to separate the top and bottom part so they do not interact.
3.1. **Convolution between frequency and space**

Figure 3.7: Simulation test case when no USAF target is present. (a) This is the band just before the transmission grating which disperses vertically. (b) Each wavelength is dispersed vertically. As along a vertical line the wavelength is equal, the whole line is shifted up. (c) The vertically dispersed band squeezed together onto a line by the camera lens. In the simulation this operation is simulated by summing the rows and rescaling the image colours.

Figure 3.8: Simulation test case where a USAF target is present. (a) This is the band just before the transmission grating which disperses vertically. (b) Each wavelength is dispersed vertically. As along a vertical line the wavelength is equal, the whole line is shifted up. (c) The vertically dispersed band squeezed together onto a line by the camera lens. In the simulation this operation is simulated by summing the rows and rescaling the image colours.
The experimental results are presented in Fig. 3.9. In Fig. 3.9a the result of the case without the blocking USAF element is shown. What can immediately be seen is that compared to Fig. 3.7c the image looks upside down, this is because in the simulation the flipping along the axes due to the lenses was not taken into account. Figure 3.9b shows the result when the largest square on the USAF target was used to block part of the spectrum. As can be seen both the figures coincide with what was expected from the simulations. In the last figure, Fig. 3.9c, it is shown what happens if most of the spectrum is blocked using the slit. Only the wavelength corresponding to a tint of green was left. As there was almost no convolution in this case, the gap induced by the square on the USAF target could be seen clearer.

![Figure 3.9: Experimental results for the one-dimensional convolution experiment. (a) No pattern blocking the spectrum. (b) A square on the USAF target blocking the light. (c) A square on the USAF target blocking the light and setting the slit to block most of the other wavelengths.](image)

With this experiment it was shown that when light sources emit wavelengths close to each other, it is difficult to clearly discern the information in all the different wavelengths.

### 3.2. Existing Spectral Imaging Techniques

As was concluded in the previous section, convolution between space and frequency could pose difficulties when data needs to be acquired. Hagen et al. [14] have done a thorough review on most of the spectral imaging techniques used, the article stems from 2013. This article was used in this section as the main source of information. Spectral imaging can be divided into two categories: scanning techniques and snapshot techniques. In this section some existing applications on spectral imaging will be discussed for both categories. The methods will not be discussed in great detail, but rather a categorisation is made for the principles used for the different spectral imaging devices.

#### 3.2.1. Sequential Scanning Techniques

For a given frame of interest, a scanning technique captures only part of this frame each time. This can be stepping in space, or having the whole space captured at once but capturing one wavelength at a time. By stitching together multiple measurements the whole data-set can be obtained. This means that the final result consists of measurements that were done at different instances in time. The scanning technique avoids the problem of having overlap in the image by only measuring in 2 of the 3 dimensions and scanning along the third or measuring just in one dimension and scanning in the other 2 dimensions. The three methods that will be discussed are point-scanning, push-broom and tunable filter. These are summarised in Fig. 3.10.
3.2. EXISTING SPECTRAL IMAGING TECHNIQUES

(a) Point scanning.  
(b) Push broom.  
(c) Tunable filter.

Figure 3.10: Categories of sequential scanning spectral imaging techniques.

POINT-SCANNING  
In point-scanning the spectrum at a specific point will be measured, this is also called confocal detection as a point is mapped onto another point. To obtain the full image, the space is scanned in 2 directions. A pinhole can be used to make sure that only the information from that point is taken into account, and then passing this through a grating to get the spectral information. A spectrometer can be used directly instead of using the pinhole and the grating. The point-scanning is graphically shown in Fig.3.10a.

PUSH-BROOM  
In the push-broom technique the spectrum on a line is measured at once. It works just as a push-broom (hence the name) as it collects everything on one line. To obtain the full image, the broom is pushed to sweep across the other places. Since the measurements are from just one line, the axis for frequency and space can still be separated. The push-broom technique is summarised in Fig.3.10b.

TUNABLE FILTER  
In this approach one frequency is captured for the whole 2D spatial domain at the same time. After doing the measurement, a filter is changed to allow for the measurement of another wavelength. Figure 3.10c shows a possible implementation for the tunable filter method.

3.2.2. SIMULTANEOUS SNAPSHOT TECHNIQUES  
As opposed to the scanning techniques, the snapshot techniques captures all 3 dimension (two-dimensional space and frequency) at once. As this will cause overlap, the solutions are more complex than for the scanning techniques. The strategy used in most of the approaches is to somehow reduce the size of the dimensions captured by a measurement device. The techniques can be divided into 3 categories: reducing the dimension of space, selecting a couple of wavelength to filter for and using techniques which allow reconstruction in the post-processing phase.

REDUCING SPATIAL DIMENSION  
This approach converts an object that would be in 2D space into an image that is 1D. In Fig.3.11a a fibre bundle with one circular end and one flat end converts a 2D image into a 1D line image. This approach would require some post-processing to recreate the 2D image in order to regain the spatial information. The fibres are brittle and are easily broken. Replacing a fibre is not so easy. Another approach is to slice the image into strips, as shown in Fig.3.11b. Each strip will arrive at its own measuring device. The difficulty in this setup is the manufacturing of the complex slicing mirror as well as the amount of measuring devices that are needed.

SELECTING WAVELENGTHS  
In this approach filters are used to limit the amount of wavelengths that are captured. The filters can be used to direct the image to different sensors, Fig.3.12a or to a single sensor, Fig.3.12b. The more filters are applied, the more losses will occur, this limits the amount of filters that can be put into the setup. In the setup
3. BACKGROUND ON HYPER-SPECTRAL IMAGING

(a) Converting 2D into 1D using a fibre bundle.

(b) Dividing 2D space into slices with a slicer mirror.

Figure 3.11: Examples of ways of reducing the spatial dimension. Figures by Hagen and Kudenov [14]
where a single sensor is used, the problem of overlapping might arise again when too many filters are used or wavelengths chosen that are too close. The sensor itself can be a filter, Fig.3.12c. Which can be seen as a more sophisticated RGB camera. This setup is might have a lower resolution, but that is not the biggest problem. It is not possible to choose another wavelength as that would require a change of the sensor.

![Diagram of spectral imaging techniques]

**Figure 3.12:** Examples of ways of reducing the spectral dimensions. Figures by Hagen and Kudenov [14]

**RECONSTRUCTION TECHNIQUES**

In this type of technique, adjustments are made to the image that do not immediately help in reducing the overlap or prevent it at all. These adjustments act as a reference for the reconstruction algorithm. Two examples are shown in Fig.3.13. In Fig.3.13a some part of the light is blocked, because the pattern that is blocking is known, this can be used in the reconstruction. Figure 3.13b shows a setup where the dispersion is not only in one direction, the kinoform grating disperses 8 different directions. By having more information this way, the image can also be reconstructed.
3. BACKGROUND ON HYPER-SPECTRAL IMAGING

(a) Reconstruction by creating a pattern in the image. (b) Reconstruction by observing the image from different view angles.

Figure 3.13: Examples of reconstruction techniques. Figures by Hagen and Kudenov [14]

3.3. HYPER-SPECTRAL IMAGING AS PROPOSED IN THIS THESIS

As mentioned in the previous sections, for a method to be usable there should be no overlap. Overlap was prevented by removing one or more of the following: space and frequency. This lead to the need for scanning, multiple sensors or very complex systems. The method proposed in this thesis does not reduce the amount of captured wavelengths nor does it reduce the dimensions of space.

The application to be designed will be used to study flame-species in flame-fronts. Most flames encountered in practical air-breathing engines are hydro-carbon flames. The spontaneous flame emissions have peaks in the spectrum which are separated such that with sufficient dispersion, no overlap is present in the bigger structures. The spectrum from the spontaneous flame emission of a hydrocarbon fuel mixture of 80% butane and 20% propane is shown in Fig.3.14. As can be seen in the figure, there basically are 4 main structures. By employing a grating that provides sufficient dispersion, the four distinct flames will be visible.

Figure 3.14: The spontaneous flame emission spectrum of a hydrocarbon flame. (butane 80% and propane 20%)

So instead of reducing one of the dimensions, the spectral property of hydrocarbon flames are used.
4

EXPERIMENTAL SETUP

In this chapter the apparatus used in the experimental setups will be listed, the experimental setups explained and the used facilities described.

4.1. EQUIPMENT USED IN THE EXPERIMENTS

The equipment can be divided into 4 categories: the flame/light-source, the optics, the measurement devices and others. This section will not cover every individual component that was available, but rather what they were used for, why they were chosen and what their limitations are. The full list of equipment including the part number and manufacturer will be listed in Appendix A. In the appendix not only the equipment used for the actual experiment is included, but also the equipment used in the previous exploratory stages.

4.1.1. THE FLAME

The flame that was used in the experiments was fed with a fuel containing 80% butane and 20% propane, manufactured by Camper Gaz. The fuel composition is stated on the fuel can, but as the primary purpose for it is for cooking outside, the composition might not be accurate as for cooking this does not matter. The Bunsen-burner nozzle is manufactured by Usbeck and has model number 1420 [15]. A simple Bunsen-burner flame has been chosen, because this kind of flame has been studied a lot and for the proof of concept of the hyper-spectral imager a simple flame with a well defined flame-front and a steady nature was desired.

As the fuel was originally for camping purposes and the Bunsen-burner nozzle a simple one, there was limited accuracy for controlling the flame and accurate determination of the fuel air mixture was not possible. The Bunsen-burner nozzle has a fuel regulator and an air regulator, but they do not have a scale on them that indicates the air flow rate and fuel flow rate. Conclusions on properties of the flame are thus not sensible to make, as a consequence the focus will be on the hyper-spectral imager.

4.1.2. THE OPTICS

The optical equipment consists of plano-convex lenses, plano-cylindrical lenses and transmission gratings. Plano-convex lenses are circular shaped lenses with the lenses having a planar side and a spherical side. The lenses used were produced by Thorlabs. The plano-cylindrical lenses are rectangular shaped with also a planar side, but the curved side only has a curvature in one direction. This means that the light is only bent in one direction. Two types of transmission gratings are used, one having 1200 lines/mm and the other having 3039.5 lines/mm. They will be referred to as the low (spectral) resolution grating and the high (spectral) resolution grating. The low resolution grating and high resolution grating were produced by Thorlabs and Ibsen respectively.

Plano-convex lenses have been chosen as they are good at collimating and focusing, due to the good spherical aberration characteristics. The plano-cylindrical lenses are not used in the final setup. The low resolution
grating will have a less dispersion, so the focus will on the larger structures. The high resolution grating has a larger dispersion, this means that the finer structures in the spectrum can be studied.

Optics have an optimal range of wavelengths they operate in, this is dependent on the material the optic is made of and also what coating has been applied to it. For the optics used, charts that display the transmission efficiency and the percentage reflectivity per wavelength are available on the manufacturers website. The higher the transmission efficiency and the lower the reflectivity, the more photons are available to be captured by the camera sensor.

The charts for the transmission efficiency and reflectivity for the lenses are shown in Fig.4.1.

![Graph](image1)

(a) Transmission efficiency of the lenses without coating.

![Graph](image2)

(b) Reflectivity of the lenses with N-BK7 coating at 8 degrees angle of incidence.

Figure 4.1: Lens performance characteristics, source: Thorlabs [16]. The data-points near 308nm have been indicated as efficiencies at that wavelength have an influence on whether the OH peak can be recorded.

For gratings there is the grating efficiency, which describes the same as the transmission efficiency of lenses. The charts for the low resolution grating and the high resolution grating are shown in Fig.4.2. Unfortunately Fig.4.2b only shows the efficiency near the maximum efficiency wavelength of 450nm.
4.1. Equipment used in the experiments

Figure 4.2: Grating efficiencies. (a) Low spectral resolution grating. Source: Thorlabs [17]. (b) High spectral resolution grating. Source: Ibsen [18].

4.1.3. Measuring devices

Three measurement devices were used: Canon 100D, WinCamD-LCM4 and CCS-100 spectrometer from Thorlabs. These measuring devices will be referred to as (photography) camera, (beam-profiling) camera and spectrometer respectively. The terms photography and beam-profiling will be left out when there is no confusion which camera is mentioned. The photography camera is an entry level Digital Single Lens Reflector camera having a RGB CMOS APS-C sensor. The lenses used for digital cameras are coated to reject ultra-violet light. This is to maximise the dynamic range of the sensor for visible light. The dynamic range is defined as the difference between the lightest and darkest part that can be simultaneous captured. Because of the coating the OH peak near 308nm can not be observed using the photography camera.

The beam profiling camera is used for analysing laser beams, the camera comes with Neutral Density (ND) filters to weaken the incoming light. These filters however can be removed to maximise the amount of photons reaching the sensor. Because the image can be focused directly on the sensor, there might be a chance of capturing the OH peak, as the sensor should be able to work in the range 355 – 1150nm for the standard model [19]. There is a model of this camera which can detect UV with a wavelength as short as 190nm, however this requires a special filter that converts UV-light into visible light. In a recent investigation by the manufacturer, lasers with lower wavelength have been tested on the sensor. The sensor now is rated to be able to register wavelengths as short as 266nm [20], it was not mentioned however what intensity the light needed to be. The official charts for the quantum efficiency only range from 400nm - 1000nm and is shown in Fig.4.3. The quantum efficiency is a measure of how well the sensor can turn light from a certain wavelength into electrons.

The beam profiling camera also has a c-mount, with this mount an adaptor can be attached to allow for mounting of Nikor lenses, which are normal photography lenses used on Nikon camera.

The last measuring device is the spectrometer. This spectrometer is designed for wavelengths between 350nm and 750nm, this means that the OH peak near 308nm will not be captured on this spectrometer. The spectrum recorded by this spectrometer will be used to calibrate the images produced by the cameras, as no better calibration method was available.
4.2. EXPERIMENTAL SETUPS

In this section the experimental facilities that were used are discussed as well as the optics arrangements (the hyper-spectral imager).

4.2.1. EXPERIMENTAL FACILITIES

The experiments need to be carried out in a room that is pitch dark, because the emitted light from the chemiluminescence is weak. Furthermore, there are factors attenuating the light-intensity. These factors are for example the light being emitted uniformly in every direction, the optics having a transmission efficiency and the camera sensor having a limiting sensitivity. As a consequence, it is important to reduce the background noise as much as possible.

The experiments were conducted in a soldering room, as the combustion testing facilities were not ready. This room could be made pitch dark. There were also a few challenges as the room was not intended for combustion experiments. The smoke alarm needed to be turned off every time an experiment was done with an open flame. Another problem was that there was no active ventilation. The combustion products might contain toxic species such as CO. To prevent health issues, the experiments could only be ran for a short time after which the room needed to be aired for a few minutes.

The facilities were not optimal to perform combustion experiments, but with some improvisation and safety measurements they were possible.

4.2.2. OPTICS ARRANGEMENTS

Two setups have been created for the measurements: one consisting of the high resolution grating and one employing the low resolution grating. This section will discuss the design choices in making these two setups. The setups as shown are not fixed, in the sense that during experiments adjustments to the setup were made to tailor to the needs. These variations will be discussed as well, but no graphical representation of these modified setups will be shown.
HIGH SPECTRAL RESOLUTION GRATING SETUP

The setup has been documented in CATIA, a Computer Aided Design program. A render created with CATIA of the high resolution grating setup is shown in Fig.4.4. As mentioned in the equipments section, the optics and measuring devices might not be optimal for the spectral range where the OH peak is present. With the optics available the most optimal setup possible is created by using the beam profiling camera and the high resolution grating, but it is not certain it can be done.

Figure 4.4: Experimental setup with the high resolution grating.

The flash-light on top of the Bunsen-burner is used for the focusing of the camera. The top half of the flash light will be covered with a piece of cardboard with a sharp edge. On the camera this edge should be made as sharp as possible. In this setup, the focus is done manually by turning the knob on the translation stage and looking at the live view on the computer. When the real experiment starts, the flash-light is removed.

The setup consists of a collecting lens with a focal length of 300mm, which collimates the incoming light. The collecting lens is followed by the high resolution grating under an angle of more than 60 degrees. Because the grating has such a strong dispersion, no dispersion would be visible if the grating were not put under such a large angle. This can be easily checked using the grating formula. After the grating a set of lenses is placed to focus the image on the sensor. The lenses have been stacked in this way to create an equivalent lens with a shorter focal length, as the shortest focal length lens available was 100mm. The combination of the focusing lenses and the 300 mm collecting lens resulted in the greatest de-magnification that could be achieved. The de-magnification is needed to fit as much as possible on the camera sensor.

The mounting base on which the camera is standing is mounted such that it can translate in the direction perpendicular to the translation stage. In this way the image can be scanned over since the dispersion by the grating is so large that not all peaks can be captured on the sensor.

LOW SPECTRAL RESOLUTION GRATING

In Fig.4.5 the experimental setup with the low resolution grating is shown. The dispersion of the low resolution grating is such that no scanning is required to get the whole picture. Due to the lower dispersion it has two first orders. This property has been used to position both the photography camera and the beam-profiling camera. The photography camera captures both the first order and the zeroth order, this gives a reference for what is seen in the first dispersed order. In this setup also a 300mm collecting lens is put in front of the grating. An advantage of using the 300mm instead of for example the 100mm lens is that it is certain that the camera captures what the collecting is capturing. If the camera is tilted a bit, it might capture part of the light that lines up with the camera lens. When the object is far enough away, this is less likely to happen, and if it happens the effect is less severe. Figure 4.6 illustrates what is meant by the zeroth order going through
Figure 4.5: Experimental setup with the low resolution grating.

Figure 4.6: By placing the object outside the field of view of the camera, the camera will not capture the object directly. This is a problem since the zeroth order can pass through the transmission grating undisturbed. Instead, the object as seen by the collimating lens is now imaged by the camera.

straight and the need of placing the object outside this range. The object seen as zeroth order by camera is not the same as seen by the collecting lens.

The spectrometer is put on a slight angle with respect to the optical axis of the collecting lens, as the zeroth order was already reserved for the photography camera. This angle is about 20 degrees.

The beam-profiling camera is now equipped with the c-mount-to-Nikon adaptor and a Nikon AF-S 35mm lens. Since the adaptor was not made for the beam-profiling camera, the Nikon lens focuses the image behind the sensor. This could not be corrected by turning the focus-ring on the Nikon lens. The solution to this problem was to place a 300mm plano-convex lens in front of the Nikon lens.

**Modifications**

Due to the limited capability of the current nozzle to produce a perfectly laminar flame, a small modification was made in this setup to attempt to create a more laminar flame. A more laminar flame was created by elongating the nozzle by using a metal tube of 0.5m. Due to the increase in tube length, the Bunsen-burner needed to be positioned lower than depicted in Fig.4.5.

Another modification that has been tested was turning the diffraction grating 90 degrees, which will result in
the dispersion being vertical. By having the dispersion vertical, the photography camera needed to be repositioned. The photography camera will be moved in front of the grating, positioned a bit higher than the grating with the lens pointing down. The beam-profiling camera will be omitted in this modified setup.

4.3. TAKING MEASUREMENTS

The methodology of the measurements of both setups and the reason for the measurements will be discussed in this section. Apart from the actual flame measurements, also a quantification measurement was done on the resolution of the total optical system.

4.3.1. RESOLUTION OF THE OPTICAL SYSTEM

The resolution was determined by putting a flash-light at the location of the flame. Then by covering a portion of the flash-light with an object having a straight edge, this sharp edge will be also present in the image. By determining how many pixels it takes to go from complete darkness to the full-brightness of the light-source, the resolution can be determined.

4.3.2. HIGH SPECTRAL RESOLUTION GRATING

This setup was mainly used to investigate whether it was possible to identify the OH peak near 308 nm. The scanning was performed by sliding the camera. The camera was connected by a USB 3.0 cable with a laptop that has the software installed. With this software package a live preview is available, allowing for direct assessment of the frame. The frame can then be exported to a comma separated file to be post-processed using MATLAB. Apart from moving the camera, all other components are left untouched.

4.3.3. LOW SPECTRAL RESOLUTION GRATING

The purpose of this setup was to demonstrate using the narrow-band feature of the hydrocarbon flame, whether it is possible to have clean distinct flames at different locations due to the different angle in dispersion. The OH peak in this setup will not be taken into account, whether or not it is going to be visible.

Ideally, all measurement devices should start recording at the same time and finish recording at the same time. Then the captured data would correspond to exact the same flame. The measurement devices have different sensitivity and thus require a different exposure time. Also even when the exposure times are the same, the three devices are controlled through one laptop it is not possible to press the buttons at the same time. However, it was made sure that the measurements were as close as possible.

The reason for putting a spectrometer in the setup is to have the spectrum of that particular flame of that time, so afterwards the spectrum can be put on top of the dispersed image.

Measurements were done with the flame as is, and also a few cases where the flame was modified. The two modifications that have been investigated were:

- Blocking the flame by putting a plate on top
- Creating a V-flame by anchoring the flame on a rod

The two modifications were done in the setup where a tube extension has been applied, the V-flame setup was only performed on the vertical dispersing grating. The blocking plate was used to create a boundary that was easily recognised in the image and the V-flame was an attempt to create a two-dimensional flame to limit the draw-back of a line-of-sight technique. Which was that the flame-fronts located at other planes were visible in the image.
In this chapter the results acquired using the setups and methodology mentioned in Chapter 4 are presented and analysed. The results will be covered by the grating type, high resolution grating and low resolution grating respectively. First of all the spatial resolution for both setups will be determined. The spectral resolution will be determined in the section of the corresponding setup.

5.1. Optical Resolution

For both setups the photography camera has been used for the determination of the resolution. This is to have consistent results and the photography camera has a better digital resolution than the beam-profiling camera. The sensor size of the photography camera is 22.3 x 14.9mm with a total resolution of 5184 x 3456 pixels [13], corresponding to a pixel size of 4.3 x 4.3 µm. The beam-profiling camera has a pixel size of 5.5 µm [19].

For the line-spread function of the low resolution grating setup Fig.5.1a has been used to determine the edge response and the line-spread function. The line-spread function is defined in this thesis by the full width half maximum of the derivative of the edge response. The colour image was first converted to a grey-scale image. At a horizontal location of 1200 pixels the intensities along the vertical pixels range 1500-1550 pixels was plot, as shown in Fig.5.1b. The linespread function was determined to be 6 pixels, corresponding to an optical resolution on the image plane of 25.8 µm. In order to determine the smallest structure that can be observed in the flame, the optical resolution at the image plane need to be multiplied with the magnification factor of the image. This magnification factor can be determined by using the diameter of the flashlight. The diameter of the flashlight is 30mm, the diameter on the image is 373 pixels which correspond to 1.6mm. The magnification is 18.75:1, this makes the smallest size in the flame that can be observed to be 0.48mm. The camera lens focal length was 18mm, which would have resulted in a magnification of 16.67:1, the image might have been stretched due to alignment.

For the high resolution grating setup the same procedure has been followed. The original image used for the edge response is shown in Fig.5.2a. The only difference with the low resolution grating setup is that the colour image has not been turned into a grey-scale image. The blue component of the image has been taken instead, as this smoothed the edge response. As the image is mostly blue, there is not much loss in information. The horizontal pixel location along which the edge response is taken is 3000, the vertical range ranged from 2400-2600 pixels. The edge response and line-spread function are shown in Fig.5.2b. The optical resolution is 34 pixels, which corresponds to 187 µm. The camera lens setting in this case was 55mm, this means that the magnification factor used in the low resolution case can not be used directly. When the magnification obtained in the low resolution grating setup is extrapolated from a 18mm lens setting to a 55mm lens setting, this will result in a magnification of 6.14:1. If the actual focal lengths are used this would result in a magnification of 5.45:1. The resolution in the flame would lie in the range of 1mm to 1.1mm.
5. RESULTS AND DISCUSSION

Figure 5.1: Determination of the line-spread function for the low resolution grating setup. (a) The original photo used for the edge response. The white lines indicate where in the original photo the edge response has been taken. The red lines indicate the width of the flashlight in pixels. (b) The normalised edge response shown in blue and the normalised derivative of the edge response shown in red. The PSF is defined as the full width at half the maximum of this derivative.

Figure 5.2: Determination of the line-spread function for the high resolution grating setup. (a) The original photo used for the edge response. The white lines indicate where in the original photo the edge response has been taken. (b) The normalised edge response shown in blue and the normalised derivative of the edge response shown in red. The PSF is defined as the full width at half the maximum of this derivative.
5.2. SPECTROMETER MEASUREMENTS

Before going into the dispersed images, the spectrum as captured by the spectrometer is discussed. The peaks and bands are compared to literature to identify them. The flame used for the spectrum measurement is the flame without any modification. The location the spectrometer was pointing at was the bottom left of the flame-front, this is indicated with a red circle in Fig.5.3. The integration time for the spectrometer was 8 seconds, which is about 20 times longer than the exposure time on the camera. The average exposure time used on the camera was 0.4 seconds.

![Image of flame with spectrometer location](image)

The papers by Zizak [21] and Fazekas et al.[22] have been used as a reference to identify the peaks in the spectrum. The identified spectrum is shown in Fig.5.4.

![Chemiluminescence spectrum of a butane/propane flame](image)

This spectrum was validated against results from the paper by Zizak et al.[21]. The results of the comparison are shown in Fig.5.5 and Fig.5.6. The validation has been performed by matching the horizontal wavelength axis.

As can be concluded from both pictures, the peaks correspond within 1nm with the validation data. The mismatch for the two $C_2$ peaks are larger than that of the rest. For the accuracy of the proof-of-concept spectral imager, the spectrometer is accurate enough and no calibration will be done on the spectrum.

The unknown specie at 588.9nm could not be identified and needed some more investigation. This peak was not always present. Gaddam et al. [23] have done a research on emissions in different bio-fuels using plasma-spectroscopy. In their research they have identified the peak at 588.9nm as atomic carbon, $C$ (II). As they have been investigating bio-fuels, the fuel does not only contain the atomic species $C$, $H$ and $O$ but might also contain other species such as Na, which has a peak very near the peak identified as $C$ (II). They have also used carbon black as fuel to generate a reference, in this fuel only carbon is present and still shows the peak.

The fuel used in the thesis is a mixture of butane and propane, 80% and 20% respectively. It is thus unlikely that the mixture will contain species other than $C$, $H$ and $O$. So the Atomic Spectra Database [24] has been
Figure 5.5: Validation of the spectrometer used in the experiments with data from Zizak et al.[21] The peaks/bands near 470, 516 and 560nm are compared. The dark blue line is the validation data and the light blue line is the data as obtained by the spectrometer.

Figure 5.6: Validation of the spectrometer used in the experiments with data from Zizak et al.[21] The peaks/bands near 430nm, 470nm and 516nm are compared. The dark blue line is the validation data and the light blue line is the data as obtained by the spectrometer.
consulted, to see whether other atomic species also emit at 588.9nm. The species that were queried were C, O and H. From this search the atomic C (II) was the most probable candidate.

5.3. **HIGH RESOLUTION GRATING SETUP**

One of the main goals of the high resolution grating setup with the beam-profiling camera was to investigate whether the OH peak near 308nm could be observed. Unfortunately this was not the case. The possible bottlenecks were: the lenses, the grating and the camera. The lenses were optimised for the range 350nm to 700nm, as seen from Fig.4.1 the transmission percentage at 308nm is 54.8% and the reflection at an angle of incidence of 8 degrees was 25%. The alignment error might not be as big as 8 degrees, but there certainly will be an alignment error as the lenses were fixed manually. For the purpose of demonstrating the losses through the lenses, the reflectivity value for 8 degrees angle of incidence will be employed. In the setup, 4 lenses were involved. Resulting in the transmission of light at a wavelength of 308 nm to be $(0.548 \cdot (1 - 0.254))^4 = 0.0279$. Due to the lenses alone, only 2.8% of the light at 308nm passes through.

The grating itself does not come with a graph showing the efficiency below 400nm. The efficiency at 400nm is 80% and has a down going gradient in the direction of the shorter wavelengths. It can be concluded that the efficiency is certainly below 80%, when extrapolating the graph, the value would be around 40% at 308nm.

The manufacturer of the beam-profiling camera also does not provide any data on the quantum efficiency below 400 nm. The quantum efficiency at 400nm is 32% and also shows a down going trend when in the direction of the shorter wavelengths. Extrapolating would result in a quantum efficiency of almost zero. According to a blog post by the manufacturer of the high resolution grating the detection of a 266 nm laser was possible [20]. The laser is a lot stronger than the flame emissions, which were already attenuated by the lenses and the grating.

The second result from this setup were images captured by the photography camera. These images are presented in Fig.5.7.

The images have been fitted with the corresponding spectrum as measured using the spectrometer, the spectrum corresponds just to one point. The peaks of the spectrometer were matched with the left edges as recorded on the image. The edges have a higher intensity because the technique is a line-of-sight technique. This means that the intensity captured by one pixel will be the integrated value along the line of sight.
Figure 5.7: Dispersed flame emissions with the high resolution grating captured with the photography camera. The brightness of the images have been increased for the visibility.
As seen from Fig.5.7 the spectra match quite well with the images, to be exact, the edges match well with the peaks in the spectrum. However, there is one peak that is a bit off. In Figs.5.7a and 5.7c the spectrum graph shows 2 peaks of C₂, but it is not visible in the image. This might be due to the fact that the angle between the peaks are too large for the camera lens, thus the camera lens is the limiting factor for the field of view. This field of view is different when imaging diffuse objects, as diffuse objects emit light in all directions. The dispersion created by the grating however is only going in one direction, this means that even though the light ray passes in front of the camera lens, the lens will not be able to capture it. This is illustrated in Fig.5.8. In Fig.5.9 the grating formula is used to calculate the dispersion angle of the first order for different wavelengths. The wavelength range taken was based on Fig.5.7c. As can be seen from the figure, the total angle the camera lens has to capture for an angle of incidence of 70 degrees on the grating was 33 degrees. The total angle at an angle of incidence of 80 degrees is 26 degrees. By increasing the angle of incidence the smaller the dispersion angle range is. With a smaller range more can be captured by the camera.

Figure 5.8: The camera lens limits the captured dispersion.

Figure 5.9: Effect of the angle of incidence on the angle of the dispersed first order.

Figure 5.10 shows the dispersed flame emissions fitted to it the spectrum as captured by the spectrometer, by adjusting the camera position and the grating orientation it was possible to have 3 bands captured.

Figure 5.10: Dispersed flame emission: CH peak and C₂ peaks. This image has been obtained with the grating at a larger angle of incidence. The brightness has been increased for better visibility.

There is however a mismatch in the spectrum and the image of the dispersion. The first two bands are matched quite well, however the third band is off. It looks as if the longer wavelengths get dispersed more than the shorter wavelengths. The fact that the increase in dispersion angle is not constant can be seen from the grating formula which consists of a sine function. While the dispersion is not constant over the wavelengths, the spectrum recorded by the spectrometer is.

In Fig.5.11 a graph is shown for the dispersion angle for the first order per wavelength. This curve was created using the grating formula. The derivative of the curve is also shown and an additional tangent line was
drawn, this line represents the dispersion angle curve when the change in dispersion angle per wavelength is constant. It can be observed that the range between 430 - 480 nm is close to the linear case. For the graph the starting wavelength was chosen to be 430nm as the CH peak at 431.1nm was used as the first reference point for the matching of the spectrum and the image.

![Disperssion Angle Graph](image)

Figure 5.11: Dispersion angle per wavelength as calculated using the grating formula, with a grating of 3309 lines/mm and an incidence angle of 70°.

To illustrate whether the non-linear dispersion is the main cause of the discrepancy a simple calculation was performed. There are two ways to approach this, trying to adjust the image to match the spectrum or to adjust the spectrum and check whether it matches. The latter option has been chosen as the spectrum gives a precise point. When looking at Fig.5.10, the peak at 516.4nm needs to be around 521nm. Since 430nm was the datum point for the tangent line, the peak at 516.4nm should be scaled also with respect to this point. For simplicity the amount to scale has been taken to be the ratio between the actual value and the value of the tangent at 516.4nm. This gives:

\[
516.4 - 430 \cdot \frac{50.27}{47.6} + 430 = 521.25
\]

Which is very close to the location in the image. This however, does not mean that this is the only effect affecting the mismatch. More investigation might be needed, but will not be covered in this thesis.

The spectral resolution of this setup is determined using Fig.5.10. The two peaks used as reference are the peak at 431.1nm and the peak at 473.5nm. These correspond to pixel 807 and 2680 in the horizontal direction. This gives a spectral resolution of 0.02nm/pixel.

5.4. LOW RESOLUTION GRATING SETUP

In this section the results obtained by using the low resolution grating are discussed. In Fig.5.12 the results for all the setups used are shown which were made with the photography camera.

Figure.5.12a was the setup as shown in Fig.4.5 without any modifications. Figure 5.12b shows the results for the setup where a tube has been added to the Bunsen burner to allow the oxidizer and fuel to be mixed better, no additional modifications were done on this setup. If the figure without tube and with tube are compared, the case with the extension has a steadier flame. This can be seen by looking at the flame-front at the sides, they remain distinct further downstream. The flame with no extension became turbulent, the flame-front at the edges blended in and were no longer visible. The image without tube extension has been stretched in vertical direction, so the actual flame is smaller. However, when only the part is studied near the end of the nozzle, there is not much of a difference.
5.4. LOW RESOLUTION GRATING SETUP

(a) No modification to the Bunsen burner.

(b) Added a tube to the Bunsen burner.

(c) Added a tube and a plate.

(d) Added a tube and created a V-flame using a metal rod.

Figure 5.12: Results for the different setups using the low resolution grating. Each image has been obtained using the photography camera and is matched with the spectrum obtained with the spectrometer. The brightness of the images have been increased to enhance the visibility.
In Fig.5.12b the several peaks can not be seen, as they overlap each other in such a way that they blend into each other. In order to distinguish the different peaks, a plate was put on top of the flame to block it. By blocking the flame while it had not burnt completely yet, a flame-front formed at the metal plate. This flame front can then be used to identify the different peaks in the spectrum. Because there was only 1 flame-front in the direction perpendicular to the flame and as this flame-front was longer than the flame width, these lines could be seen distinctly in the image.

There is a red glow in the flame near the plate under the flame-front created by the plate. At first thought it might have been soot, but soot is emitting a broadband spectrum, as can be seen in Fig.5.13.

![Figure 5.13: Soot emitting a broadband spectrum. The soot was created by introducing a burnt match in the flame.](image)

This red glow was not present when the flame was lit, neither was the peak in the spectrum at 588.9 nm. For this reason, the red glow can be attributed to the peak at 588.9nm. When the flame was just lit the plate was cold, it might be that the reaction creating the red glow needs to have a certain activation temperature for this chemical reaction to occur. In the kinetics database by the National Institute of Standards and Technology (NIST) [25] known chemical reactions can be looked up. The database has been queried for chemical reactions that have carbon as reaction product. In the search results there is an indication at which temperatures each reaction takes place. The typical flame temperature of a butane/propane mixed flame is 1970 degrees Celsius [26] or 2243K. All reactions that include species that are present in a hydrocarbon flame or in the ambient air and those that are below 2243K are listed below.

\[
\begin{align*}
CN + O &\rightarrow C + NO \\
CN + N &\rightarrow C + N_2 \\
CH + CH &\rightarrow C + CH_2 \\
CH + H &\rightarrow C + H_2 \\
CH + N &\rightarrow C + NH \\
CH_2 &\rightarrow C + H_2
\end{align*}
\]

As can be seen from Fig.5.12c, starting from 520nm the peaks do not match anymore. A similar approach was taken as for the case from the high resolution grating setup, to check whether the non-linear dispersion of the grating explained the mismatch, or if other factors might have played a role.

The peak at 563.4nm should be on 566.5nm to match the image, again this reversed approach was chosen as the value at the peak is easier to identify. Figure 5.14 shows the actual dispersion angles and the case where the scale is linear.

The same calculation was performed:

\[
\frac{563.4 - 430}{41.77} + 430 = 565.9
\]
Figure 5.14: Dispersion angle per wavelength as calculated using the grating formula, with a grating of 1200 lines/mm and an incidence angle of 0°.

Now also a calculation was performed on the peak at 588.9 nm:

\[ (588.9 - 430) \cdot \frac{44.97}{43.82} + 430 = 593.1 \]

On the wavelength axis, there should be another 6nm added to the corrected location for the peak because the red glow was below the edge where the other peaks were matched to. This resulted in that the spectrum would be at 599.1nm while the image is at 600nm. Although the results were close, there remained a mismatch. Another factor might be the orientation of the sensor with respect to the dispersed wavelengths. Because all the wavelengths come in at a different angle, the path-lengths will differ. This is shown exaggerated in Fig.5.15. The extra path-length will cause a skewing effect on the image.

Figure 5.15: Dispersed light reaching the sensor at different angles. This creates different path-lengths and skews the image.

The last result as seen in Fig.5.12d is the V-flame. This flame was created by putting a metal rod in the flame, the flame was anchored on the metal rod. Since the hyper-spectral imager is a line-of-sight technique, the more photons packed together, the brighter the signal will be. The V-flame accomplishes that since the flame can be considered to be two dimensional. In this setup, the individual peaks in the 4 main structures can not be discerned individually, but the structure as a whole can. Furthermore, the 4 structures could all be separated, none of them were touching each other.

The spectral resolution of this setup is determined using Fig.5.12c, because the edges in the image are clear. The two peaks in the spectrum that were used as reference were the peaks at 431.1nm and 473.5nm. The horizontal pixel locations corresponding to the two peaks in the image are 3258 and 3537. This results in a
spectral resolution of 0.15nm/pixel.

5.4.1. Comparing the Beam-profiling Camera and the Photography Camera

In the setup where no modifications were made to the Bunsen-burner, the beam-profiling camera was operational. Figure 5.16 shows the image captured with the beam-profiling camera. Compared to Fig.5.12b, which was taken with the photography camera, the image with the beam-profiling camera has less contrast.

![Figure 5.16: Image captured with the beam-profiling camera with the low resolution grating setup as shown in Fig.4.5.](image)

The pixel bit depth of the beam profiling camera is 12 bit, which means 4096 steps from black to white. This range however is not fully utilised, but the image displays this range. The unmodified image is shown in Fig.5.17a. According to the histogram, the bit depth should be 14 bits instead of 12 bits. By capping the pixel intensity to 7000, the image appeared lighter. This is shown in Fig.5.17a. Although the contrast has improved, it is still not as good as in Fig.5.16.

![Figure 5.17: Contrast improvement for the DataRay image.](image)
5.4.2. Creating a Three-Dimensional Hyper-Spectral Data Cube

As the wavelengths are not separated in a hard way as with the other spectral imaging methods, such as with filters. It is harder to create a data cube from the image. An attempt has been made to do it with the result from the V-flame. The image of the V-flame has been chosen as the dispersed flames are well separated. Although the individual peaks in a band are still overlapping, the dispersion is with this grating small enough to consider them as one.

The method used to build the data cube is a manual one. The image is rotated manually so that vertical location can be kept constant. Then the horizontal locations for the areas to be taken into the data cube are manually selected.

The areas that have been taken are shown in Fig.5.18 in which also the corresponding location in the zeroth order is indicated.

![Figure 5.18: Locations that were taken for the construction of the three-dimensional data cube and the corresponding location for the zeroth order.](image)

The frames that were selected in Fig.5.18 are shown separately in Fig.5.19. Although the V-flames are separate, but the frame size has been taken too large. This can be for example seen in Fig.5.19b, in which in the top and bottom right corners the flame corresponding to a wavelength of 473 nm can be seen.

![Figure 5.19: The frames as selected in Fig.5.18 shown separately. The dispersed frames have been increased 1.5 times in brightness for visibility. The wavelength corresponding to the frames are indicated in the figure. The red circle in the zeroth order image indicates the location taken to show the spectrum at that point.](image)

These separate frames can be stacked together to form a three-dimensional data cube. The data cube is visualised in 3 dimensions in Fig.5.20.
The data cube can then be used to for example look up the spectrum in a certain point. To show this, the point indicated with a red circle in Fig.5.19a has been chosen. The result is shown in Fig.5.21 with the spectrum recorded with the spectrometer on top. In order to produce the bars, the frames have been converted to a grey scale image first. It is a coincidence that the peaks have the same magnitude distribution as the spectrometer, that is that the largest peak correspond to the largest bar. In general the sensitivity of different sensors to certain wavelengths are different and should be calibrated for first. The first frame corresponds to the lower peak near 430 nm.

In order to see how well the cube frames match, they were merged into one figure. The RGB colours were added together. Then the merged image was compared with the image as gotten from the zeroth order. This is shown in Fig.5.22.

As can be seen from the figure, the merged image looks much more blue than the original. This might be due to the addition and scaling of the merged image and also the fact that a lot of red is not taken into account.
Figure 5.22: Comparison between the original zeroth order and the frames of the hyper-spectral data cube put together.
CONCLUSIONS AND RECOMMENDATIONS

This chapter concludes the thesis and will also present recommendations for future research.

6.1. CONCLUSIONS

The objective of this thesis was to develop snap-shot photography of multiple transient species in flames by recording chemiluminescence spectral information from a planar field obtained in a non-scanning procedure. Chemiluminescence is the chemical excitation and relaxation of the electrons of the species. This results in photons being emitted in the wavelengths characteristic for a chemical specie. By studying the chemiluminescence signal, species information in the flame can be obtained.

The investigated setups consisted of a collecting lens, a transmission grating, a focusing lens system and an image sensor. Two gratings with different lines per mm have been investigated, 1200 lines/mm (low spectral resolution) and 3039 lines/mm (high spectral resolution) respectively. Additionally, a spectrometer has been added to the setup to calibrate the captured image afterwards. As opposed to other spectral imaging techniques employed in this field, the entire two-dimensional frame of interest and its corresponding spectrum could be captured simultaneously. This is because the investigated setup does not make use of filters or scanning methods, but relies on the fact that the flame spectrum has distinct peaks.

The flame used for this research was a hydrocarbon flame fed by a butane/propane fuel mixture. The chemiluminescence signal of this flame was weak, resulting in an integration time for the spectrometer of 8 seconds. The sensitivity of the camera was better, but still required an exposure time of 0.5 seconds.

The point spread function at full width half maximum of the low resolution grating on the image sensor was determined to be 25.8 $\mu$m, by taking into account the magnification the smallest structure that can be observed in the flame is 0.5. The high resolution grating had a point spread function at full width half maximum of 187 $\mu$m, corresponding to a structure of 1mm in the flame.

For each of the results obtained, the corresponding spectrum by the spectrometer have been matched. The spectrometer output was validated with spectra found in literature. The spectrum did not match the image for the longer wavelengths due to the non-linear dispersion of the grating. Although the spectrum did not match at the longer wavelengths, the spectral resolution of both setups was determined by using the shorter wavelengths. The spectral resolution of the low resolution grating setup was 0.15nm/pixel and 0.02nm/pixel for the high resolution grating setup.

With the low resolution grating setup attempts have been made to modify the flame to be a two-dimensional flame, this was to counter the effects of this line-of-sight technique. Of these attempts the V-flame was the most successful, it was practically two-dimensional and the bigger structures in the spectrum were all separated. These frames have been used to construct a three-dimensional hyper-spectral data cube. Which contains information of the spectrum for every two dimensional point.

In the results an unknown specie near 590 nm has been observed, which was attributed to the red glow that
could be seen in the flame. By having the spectral data it could be concluded that this red glow is not originating from soot, which emits a broadband signal. This observation would have been made if a spectral imaging technique would have been used with filters.

Although the results could be improved in many ways it can be concluded that the snapshot flexible chemiluminescence hyper-spectral imager is a useful addition to the existing species detection techniques. This thesis proved the working principles of this technique and further research is needed to extend the limits of this technique.

6.2. Recommendations for future research

As mentioned the implementation of the snapshot flexible chemiluminescence hyper-spectral imager is not perfect. In this section a few recommendations are presented for future research:

• The exposure time of the camera used was 0.5 seconds. This is too slow to freeze and capture the flame-front structures. An investigation with more sensitive cameras is needed, as the ultimate goal is to be able to study flame fronts in detail.

• The dispersed flames corresponding to the different flame species were overlapping. Further research to obtain clean frames needs to be done. In order to reduce overlap in the area of interest the studied portion of the flame could be reduced, the magnification of the telescope decreased or a grating with a different line-density investigated. The flame emissions are currently dispersed either horizontally or vertically, investigating other angles might also help in reducing the overlap.

• The chemiluminescence detection technique is a line-of-sight technique. In this thesis attempts have been done on creating two-dimensional flames to overcome this problem. Further research is needed to implement methods of reducing the line-of-sight draw-backs to be able to study complex three-dimensional flames.

• The spectrometer was used in this thesis to attempt to calibrate the camera image. The camera should be calibrated directly instead of post-calibrating the image. The current method was not capable of calibrating the non-linear dispersion of the grating; an even more important argument is that when flames are studied with unknown spectrum, post-calibration will not be possible.

• The final recommendation is to employ optics having high efficiency in the UV domain, in order to record the OH signal.


In this Appendix, a list is provided of the used equipment. The list is divided into the following categories: optics, optical mounts, measurement devices and light sources.

**A.1. OPTICS**

Table A.1: Optics used in the experiments in this thesis.

<table>
<thead>
<tr>
<th>Name</th>
<th>Brand/Manufacturer</th>
<th>Part identifier</th>
<th>Comments</th>
</tr>
</thead>
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<tr>
<td>f100 plano-convex lens</td>
<td>Thorlabs</td>
<td>LA1050-A</td>
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<tr>
<td>f200 plano-convex lens</td>
<td>Thorlabs</td>
<td>LA1979-A</td>
<td></td>
</tr>
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<td>f300 plano-convex lens</td>
<td>Thorlabs</td>
<td>LA1256-A</td>
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<td>GT50-12</td>
<td>1200 grooves/mm</td>
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<td>Positive USAF1951 Test Target</td>
<td>Thorlabs</td>
<td>R3L3S1P</td>
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<td>Ibsen</td>
<td>PCG-3039.5-450-810</td>
<td>3039.5 lines/mm range 450-810nm</td>
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### A.2. Optics Mounts

Table A.2: Mounts used to position the optics.

<table>
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<td>TR30/M</td>
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<td>Post 50 mm</td>
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<td>TR50/M</td>
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<td>TR150/M</td>
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<td>TR200/M</td>
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<td>SWC/M</td>
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<td>PM3/M</td>
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<td>PM4/M</td>
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<td>Large V-clamp</td>
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<td>VC3/M</td>
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<td>DTS50/M</td>
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<td>Translation stage 3 axis</td>
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<td>LMR2/M</td>
<td>Circular lens mount</td>
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<td>ER1.5</td>
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<td>Post collar</td>
<td>Thorlabs</td>
<td>R2/M</td>
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<td>C For Nikon</td>
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</table>
A.3. MEASUREMENT DEVICES

The photography camera lens systems are not measuring devices. But they are only used in combination with one of the measuring devices, therefore they have been listed in this section.

Table A.3: Measurement devices used in the experiments conducted in this thesis.

<table>
<thead>
<tr>
<th>Name</th>
<th>Brand/Manufacturer</th>
<th>Part identifier</th>
<th>Comments</th>
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<tbody>
<tr>
<td>DSLR camera</td>
<td>Canon</td>
<td>100D</td>
<td>Own camera. Referred to in text as 'photography camera'.</td>
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<td>DSLR lens Spectrometer</td>
<td>Canon</td>
<td>18-55mm IS STM CCS100</td>
<td>Lens for the canon 100D Referred to in text as 'Spectrometer'.</td>
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<td>AF NIKKOR 50 mm</td>
<td>Referred to in text as 'Beam profiling camera'.</td>
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<td>Nikor 35 mm lens</td>
<td>Nikon</td>
<td>AF NIKKOR 35 mm f/2 D</td>
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<td>DataRay</td>
<td>DataRay WinCamD-LCM4</td>
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A.4. LIGHT-SOURCES

The fuel bottle and nozzle themselves are not light-sources, but combined and lit they are. Therefore this section was the most appropriate place to have them listed.

Table A.4: Light sources as used in the experiments. Not only electric light-sources but also the flame is considered to be a light-source.

<table>
<thead>
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<th>Name</th>
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<th>Part identifier</th>
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<td>692nm laser</td>
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<td>Bunsenburner nozzle</td>
<td>Usbeck</td>
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<td>Fuel bottle</td>
<td>Camper Gaz</td>
<td>1420</td>
<td>80% Butane, 20% Propane, 450g</td>
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<td>Small flash light</td>
<td>GP</td>
<td>Discovery compact</td>
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<tr>
<td>Big flash light</td>
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