# THE DEVELOPMENT OF A LOW-COST SPECTROSCOPY BASED TURBIDITY MEASUREMENT SYSTEM

Bachelor Thesis Creative Technology

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# Abstract

The quantification of the quality of the treated rainwater is crucial for its use in many applications. While there exist systems for water quality analysis, industry standard technologies for water quality analysis are expensive, often costing thousands of euros. This not only makes water quality analysis very expensive, but also inaccessible in developing countries, where measuring the quality of drinking water is especially important due to the low water quality standards in those countries.

Currently, there are very few low-cost solutions to water quality analysis therefore, this report describes the development of a low-cost turbidity measurement system, with the goal of creating a proof of concept for such a system. This bachelor thesis aims to answer the research question *How to develop a spectroscopy-based rainwater turbidity measurement system using low-cost components?"*

# Acknowledgments

There are multiple people that I would like to acknowledge as being crucial to the development of this project. First of all, I would like to thank my supervisors, namely Richard Bults and Erik faber, without whose support and guidance during difficult times this project would not be possible. Furthermore, I would like to thank Mark Leijdekkers and Joris de Grooth from NX-Filtration, for their time and useful inputs in the design process of this project. Finally, I would like to thank Alfred de Vries, for his persistent help throughout the development and testing of the systems.

# Contents

# List of Figures

# Chapter 1 – Introduction

The introduction chapter starts with the context behind the project, where the initial background information is presented, followed by an explanation of the problem statement. Next, the research question is presented, along with a few sub-questions that this thesis aims to answer. This chapter concludes with an outline of the report, where each chapter is briefly explained.

## 1.1 Context

Water is an essential resource for human life. Nevertheless, 771 million people live without access to safe water [1]. This is one of the reasons why the United Nations have included “access to clean water” as one of their 17 sustainable development goals [2].

Due to a growing population and climate change water scarcity is ever so prominent, with hundreds of millions of people taking multiple trips a day to collect water, and many relying on contaminated surface water to meet their basic needs. The need for alternative water sources and smarter use of water is a paramount step in the reduction of water scarcity around the world to achieve the UN’s sustainable development goal.

The Regentoren project [3], is one of many initiatives around the world that aims to address the smarter use of water problem. The municipality of Enschede, the University of Twente and the Water Board Vechtstromen are working together in this project to develop a network of Smart Rainwater Buffers

(SRBs). The goal of this network is twofold: 1) collect and store rainwater for future use, and 2) provide distributed rainwater buffer capacity to relieve the municipalities sewer system during extreme rainfall. A 35 $m^3$ SRB (SRB35k) was developed late 2022 with sponsoring of NX filtration and the municipality of Enschede. This SRB35k is tested early 2023 on the University of Twente's campus. The collected and stored rainwater will be used by the campus facilities management to water the plants and trees on campus and relieve the sewer system close the sports centre.
NX Filtration [4] specialises in direct nanofiltration membrane technology, which purifies water by removing micropollutants, colour, certain salts, bacteria, viruses, and nano plastics in one affordable step offering strong sustainability benefits. NX Filtration wants to treat the rainwater collected in the SRB35k by removing contaminants using their membranes, with the goal of getting clean water.

## 1.2 Problem Statement

The quantification of the quality of the treated rainwater is not only crucial for its use in specific applications, but also vital for monitoring proper working of the NX Filtration system. If the filter under performs, the quality of the treated rainwater decreases. While there exist systems for water quality analysis, industry standard technologies for water quality analysis are expensive. The related costs can be tens of times higher than the cost of installing a nanofiltration membrane system; hence, significantly increasing the cost of the entire filtration system.

The goal of this project is to develop a proof of concept, for a low-cost system that monitors water quality. While there are numerous different techniques for water quality analysis, this projects focus is on utilising spectroscopy to measure the turbidity of water.

## 1.3 Research Question

The main research question of this project is:

*"How to develop a spectroscopy-based rainwater turbidity measurement system using low-cost components?"*

In order to answer the main research question, there are three sub-questions that need to be answered during this project.

- How to develop a turbidity measurement system?
- How to utilise spectroscopy for measuring turbidity?
- How to analyse the performance of the final system?

## 1.4 Structure of Thesis

The structure of the report is as follows. Chapter 2 presents the background research, namely a literature review on different water quality analysis methods, along with an overview of how spectroscopy can be used to measure turbidity of water. Chapter 3 describes the methods and techniques used throughout this project. Chapter 4 is the ideation, where the specific stakeholders are identified and analysed, along with their specific requirements. This chapter also consists of numerous concepts, all of which are presented and discussed. Chapter 5 presents the specification of the concepts, where the specific functionality of each component is analysed. Chapter 6 is the realisation chapter, which presents the specific components used, and the way in which the concepts were realised. Chapter 7 contains the evaluation of each concept, where the results from the testing are presented and analysed. The thesis concludes with chapter 8 and 9, where the conclusion is discussed, and further recommendations for the project are presented.

# Chapter 2 – Background Research

This chapter starts with background information on water quality analysis, and an overview of the different techniques. Furthermore, a literature review on spectroscopy and the ways in which it can be applied for monitoring water quality is conducted, along with a review of related systems utilising spectroscopy for low-cost water quality analysis. Finally, the chapter concludes with a discussion and evaluation of the conducted research.

## 2.1 Literature Review

The main objective of this literature review is to gain insight into the different ways in which an accurate system for water quality analysis can be developed using affordable, off-the-shelf equipment.

### 2.1.1 Background information on water quality analysis

Before analysing different methods used for water quality analysis, it is important to understand what water quality analysis is. Bitabrata Roy [5] states that water quality analysis is to measure the required parameters of water, following a standard method, to check whether they are in accordance with the standard, while Dibo Hou et al. [6] defines a water-quality event as a time period over which water with anomalous characteristics is detected. Both these definitions rely on the measurement and quantification of certain parameters, and a comparison to a standard.

### 2.1.2 Overview different techniques for water quality analysis

There are different techniques to analyse water quality, each coming with their own benefits and limitations.

Titration

Using a titration method described by Gabriela Popescu et al. [7] requires the use of various chemicals to test the water sample and is a lengthy procedure. The analysis is performed in the laboratory, using expensive and large instruments, requiring a lot of different reagents causing secondary contamination [11].

Test Strips

Another method to determine water quality is to use strips of test paper, which are submerged in a water sample; however, colour examinations using test strips are subjective to human observation [8], and don't give a quantified result.

Electronic sensors

Electronic sensors are much more accurate at quantifying parameters but come at a high cost and require regular calibration and maintenance by trained staff [9].

Analytical methods

Different implementations of gas chromatography are very precise and accurate techniques for identification and quantification of water contaminants [10], however they are very expensive, require cumbersome equipment which needs to be maintained by skilled professionals [9].

**Other techniques**

Other techniques such as enrichment analysis, biosensor technology and electrochemical analyses technology lack in detection accuracy and require high-cost instrumentation [11]. While each of the preceding techniques are effective at performing water quality analysis, they don’t answer the research question, as they are either not low cost, or don’t utilise spectroscopy to measure the turbidity of water. Therefore, an alternative method needs to be further explored.

### 2.1.3 Spectroscopy

Spectroscopy is another emerging and promising technique for analysing water quality. This technique relies on the emission and absorption spectra of different substances [11], to quantitatively identify and determine the concentration of such substances in the water.  Spectroscopy can be broken down into two main branches [13], fluorescence and absorbance spectroscopy.

<u>Fluorescence spectroscopy</u>

Fluorescence spectroscopy involves adding a fluorescent dye to the water sample, and measuring the wavelength and intensity of the fluorescence emitted [14]. Different chemicals will fluoresce at different wavelengths, and the intensity of fluorescence determines the concentration of the chemical. This technique relies on adding a substance to the sample of water such as dansyl or fluorescein, causing secondary pollution with toxic chemicals making that water sample undrinkable [14]. While fluorescence spectroscopy can be used to measure water quality accurately and cheaply, it is unsuitable for inline analysis due to the secondary pollution of the water.

<u>Absorption spectroscopy</u>

There are many different types of absorbance spectroscopy, and they all share the basic principle of shining light of a known intensity and wavelength through a water sample and measuring the amount of light that exits the sample. Different chemicals absorb or scatter light at specific wavelengths, by measuring the absorption spectrum of a water sample, it is possible to determine the presence and concentration of various chemicals [16]. In addition, this method does not involve adding any substance to the water, eliminating secondary pollution.

One of the most commonly used techniques of absorption spectroscopic water quality analysis is UV-VIS spectroscopy, which involves measuring the intensity of ultraviolet light through a water sample. Different pollutants have different absorption characteristics, but the majority absorb ultraviolet light [11], making UV-VIS spectroscopy very effective at analysing water quality. Different ultraviolet wavelengths can be used to determine the concentration of specific particles in the water [5], allowing for very precise analysis. This technique is simple to implement in a rudimentary system, as the components are readily available and low cost in comparison to the previously described methods, and the method itself is not overly complicated.

Three different implementations of UV-VIS spectroscopy exist, namely:

- Fixed wavelength detector
- Tuneable wavelength detector
- Full spectrum detector.

Fixed wavelength detector

A fixed wavelength detector makes use of an optical bandpass filter allowing for once specific wavelength to pass through to the detector, blocking all other wavelengths[17]. This implementation is primarily used in situations where the goal is to repeatedly measure the concentration of one specific substance in the water. The main benefit of this solution is the simplicity, and low cost due to the lack of need for a precise, narrowband light source as the bandpass filter only allows a specific wavelength to pass. In addition, this technique is very accurate as the detector is less subject to noise and interference that might be caused by other wavelengths of light, which cannot be detected due to the filter.

Tuneable Wavelength Detector

A tuneable wavelength detector implementation makes use of a variable bandpass filter, that allows the selection of the wavelength that passes through to the detector. This solution benefits from the fact that multiple measurements can be performed on the same sample of water at different wavelengths, allowing for the analysis of different substances [18]. This implementation, however, is more expensive and complex than a fixed wavelength detector, due to the more advanced optical filter. In addition, the time of measurement is significantly longer, often taking a minute.

Full spectrum detector

A full spectrum detector consists of a Diode Array Detector (DDA), which detects the absorbance of light at all wavelengths in the spectrum simultaneously. This type of implementation benefits from higher versatility, as one measurement takes a few milliseconds, and yields the absorbance data for all wavelengths[17]. This allows for a very detailed analysis of the concentration of multiple substances in the water, without the need to take multiple measurements. That being said, a full spectrum detector are more expensive due to the complexity of the DDA, and the measurements of specific wavelengths are more subject to noise and therefore interference form due to all the wavelengths being present [18].

Raman Spectroscopy

Another common technique is called Raman spectroscopy, which relies on the Raman effect [20]. This technique involves shining a laser beam at a water sample and measuring the intensity of the scattered light at different wavelengths. Different chemicals produce unique Raman spectra, so by analysing the spectrum of scattered light, you can determine the presence and concentration of various chemicals. As stated by Almaviva et al. this technique "offers the distinct advantages of chemical specificity" [20], allowing for a more accurate distinction between different substances in the water. That being said, this technique necessitates the use of very precise lasers and detectors, and complicated calibration is needed, making this technique difficult to implement in a low-cost system.

Infrared Spectroscopy

Infrared spectroscopy involves shining infrared light through a water sample and measuring the absorption of the light at different wavelengths. Different chemicals absorb infrared light at specific wavelengths, so by measuring the absorption spectrum, you can determine the presence and concentration of various chemicals [21]. The key benefit of infrared spectroscopy is the speed of measurement, and the fact that both coloured and colourless water samples can be measured. This is due to the fact the visible colour of a sample has no effect on the ability of that sample to interact with infrared light[22].

### 2.1.4 Utilising spectroscopy for water quality analysis

Turbidity at its core, is the measure of the clarity of a liquid, an optical property of water. Turbidity is caused by the presence of suspended nano and micro particles such as dust, microorganisms, and any other substances that are not dissolved inside the liquid [15].

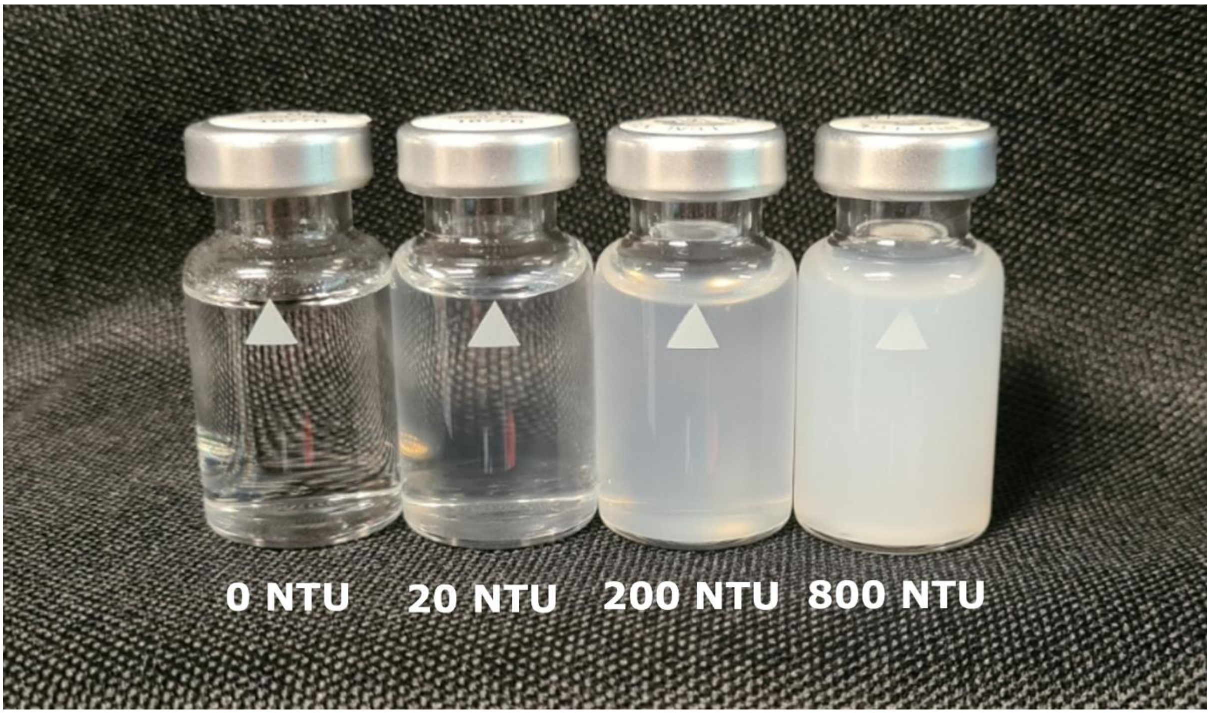


*Figure 1: Samples of water of increasing Turbidity*

The measurement of the amount of light that is either scattered or absorbed (see page 14) by the suspended particles, can be used to determine the turbidity, thus determining the concentration of suspended particles in a liquid. The optical phenomena, whether light is scattered or absorbed, is determined by the size of the suspended particles, and their properties. Therefore, there are two distinct methods of measuring turbidity by applying spectroscopy:

1) Nephelometric measurement
   This method uses a light source and a detector to measure the amount of scattered light by the suspended particles as the light passes through a water sample. Nephelometry is applied when the suspended particles are in the magnitude of nanometres. [19] For nephelometric measurements, the light source-detector arrangement is such that the detector is perpendicular to the light source, at a 90° angle (see figure 2). The higher the turbidity the more particles that are present, resulting in greater scattering of light.

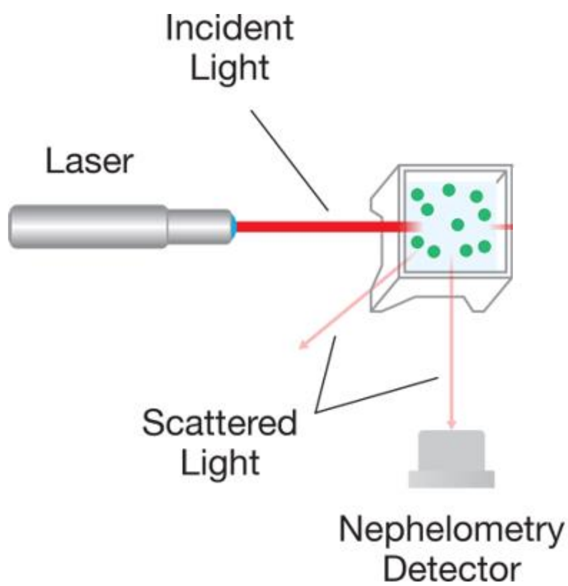


*Figure 2: Nephelometric measurement arrangement*

2) Turbidimetric measurement
   This method involves measuring the amount of light that gets absorbed by the suspended particles as it passes through a water sample. Turbidimetric measurements are applied when the size of the suspended particles exceeds a micrometre [19]. For turbidimetry, the light source

and detector are arranged in-line, such that the detector exactly faces the light source, without horizontal or vertical displacement (see figure 3). The higher the turbidity, the more particles are present, therefore the greater the absorption of light by these particles.

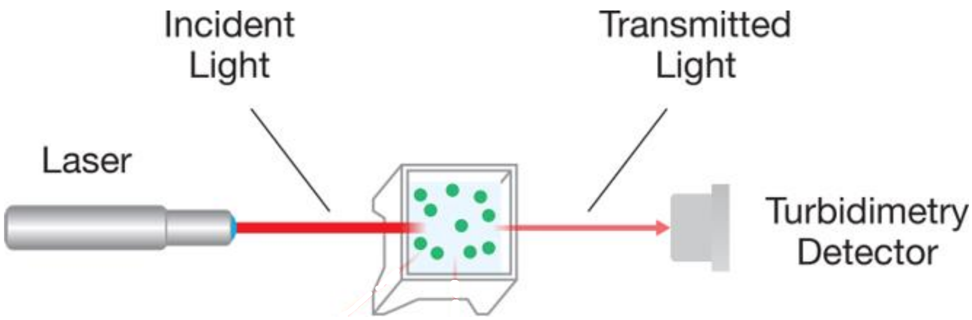


*Figure 3: Turbidimetric measurement arrangement*

### 2.1.5 Literature research conclusion

There exist multiple different types of spectroscopy, which can be used to measure the turbidity of water. Two distinct methods of spectroscopy exist, namely nephelometric and turbidimetric. Through consultation with the stakeholders (see section 4.2), it became clear that the size of the particles of interest are in the magnitude of nanometres, therefore the nephelometric measurement technique is chosen. The reasoning behind this is that the NX-Filtration specialise in direct nanofiltration, which filters out nano particles therefore, in order to monitor the correct working of the filtration system, the concentration of the nano particles needs to be measured.

## 2.2 State of the Art

This section presents two industry standard systems that utilise spectroscopy for water quality analysis, along with a related low-cost system that utilises nephelometry for measuring the turbidity of water, focusing on measuring the concentration of suspended nano particles.

### 2.2.1 Lovibond TB 211IR

As previously mentioned in section 1.2, industry standard systems for water quality analysis are very expensive, often costing more than the cost of some filtration systems. For instance, NX-Filtration uses an industry standard Lovibond TB 211IR [23] in order to measure the concentration of suspended nanoparticles, namely the turbidity of a sample of water. This device measures the scattering of infrared light of a selected 860nm (infrared wavelength) wavelength at a 90° angle. It can measure turbidity at a range of 0.01 NTU up to 1100 NTU, with an accuracy of ± 2.5%. The cost of such a device is around 1200 euros.


*Figure 4: Lovibond TB 211IR*

### 2.2.2 Van Remmen UV Transmittance Meter

Another system used by NX-Filtration, is the Van Remmen UV Transmittance Meter [24], which measures the absorption of ultraviolet light at a wavelength of 254nm. It is used to determine the transmittance of a liquid, and costs around 2000 euros

Figure 5: Van Remmen UV Transmittance Meter [24]

## 2.2.3 Related systems utilising spectroscopy for water quality analysis

Rudimentary spectroscopy can be implemented at a low cost as shown by Nayeem et. al in their paper *Towards Development of a Simple Technique based Wavelength Specific Absorption for Quality Measurement of Flowing Water* [9], where they successfully designed and implemented a system that can accurately measure multiple parameters of water utilising absorption spectroscopy using off the shelf equipment for less than 50 euros. The system can measure the turbidity of water, its PH, and the TDS (Total Dissolved Solids).

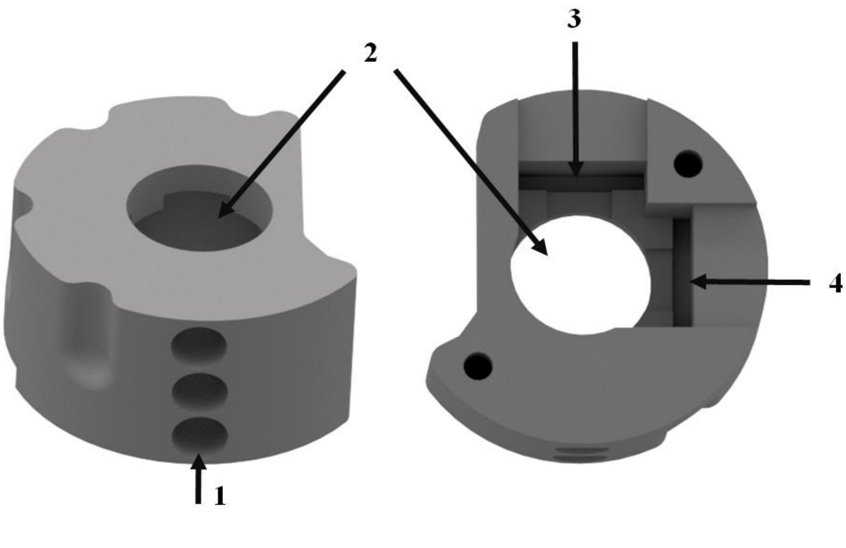


Figure 6: 3D model of the casing for the system

## 2.3 Discussion and Conclusion

The goal of this chapter was to get insight into water quality analysis, and to understand how spectroscopy can be used to measure turbidity. There exist many different techniques for water quality analysis, all coming with their own benefits and limitations. Many techniques require a chemical, like in the case of fluorescence spectroscopy. This causes secondary pollution, and makes that sample of water unusable. Other techniques require complicated and expensive equipment, going against the goal of achieving a low cost system.

The state of the art research showed that industry standard systems are very expensive, necessitating the development of a low cost system in order to reduce the cost, and therefore increase the accessibility of water quality analysis systems. There is a limited amount of low cost systems, however Nayeem et. Al showed that it is possible to develop a low cost system for water quality analysis, and therefore their paper [9] will serve as the starting point of this project.

# Chapter 3 – Methods and Techniques

This chapter describes the techniques and methods used throughout this graduation project. Different methods and techniques are vital in ensuring consistent structure throughout the design phase and the report. The core method applied for this graduation project, is an implementation of the Creative Technology Design Process (CTDP).

## 3.1 Design Method

The design process for Creative Technology (see figure 7) is based on two classical design models: the Divergence and Convergence Model of Jones [25] and the Spiral Model first described by Barry Bohem [26].

The first model consists of two phases, divergence and convergence where one always follows the other. The Divergence Phase opens up and defines the design space, allowing for an exploration of possible solutions. The Convergence Phase can be seen as a process of narrowing down the design space, ultimately reaching one best solution that is based on the available knowledge and the requirements.
The second model allows for a non-sequential order of design steps within a design phase, where each design problem spirals into a sequence of questions that relate to the initial problem.

The Creative Technology Design Process (aka CreaTe design process) [27] has four phases: ideation, specification, realisation, and evaluation. The four phases are used to answer the design question, which is the starting point of this design process. The goal of the CreaTe design process is to give a structured method for the design process of a system or product, allowing for more efficient planning and defined feedback moments.

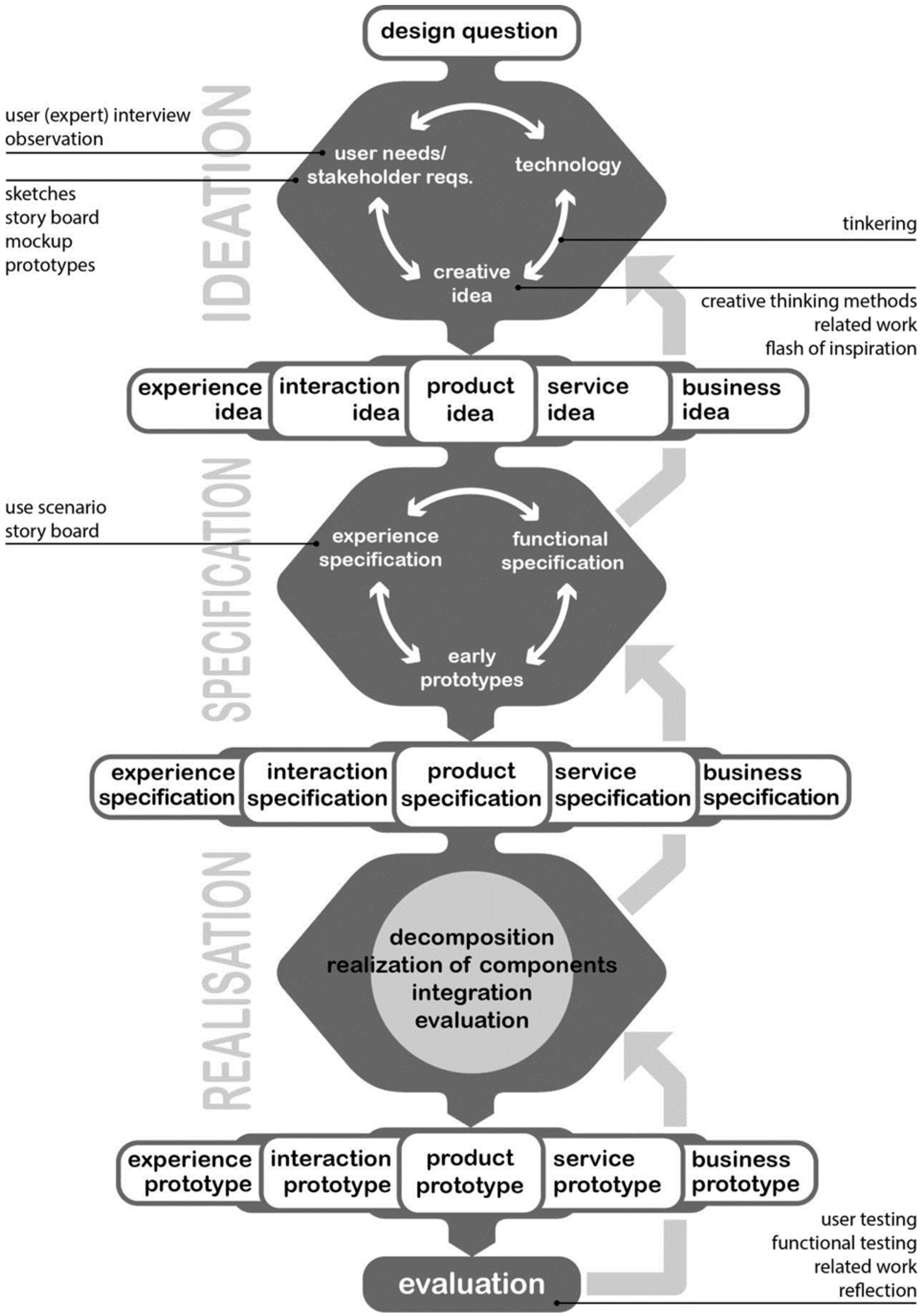


*Figure 7: Creative Technology Design Process [27]*

### 3.1.1 Ideation phase

The starting point of the design process is the design question (in the context of this report, the research question), which can either be a product idea, order from a client, or a creative inspiration and serves as the main problem that is being addressed.

The ideation phase is based on the spiral model, with the definition of the problem, acquisition of relevant knowledge and information, and idea generation following a spiral trend. The design question is then transformed into a research question, based on the knowledge gained from background research and stakeholder requirements. The research question is then further altered and verified based on the state of the art research, brainstorming, and tinkering, all of which are additional sources of inspiration to come up with creative ideas. Those early creative ideas are then discussed with the clients and relevant stakeholders, and altered when necessary. Through consultation with the stakeholders, specific functional requirements are developed, which serve as a guidance into the functionality of the final system. The result of the ideation phase is a detailed project idea, multiple concepts, and the stakeholder needs of the final system.

### 3.1.2 Specification Phase

The goal of the specification phase is to specify the functionality of the product. The starting point of the specification phase is the detailed project idea, the concepts developed in the ideation phase along with a specification and categorisation of the functional and non-functional requirements. This graduation project will use the specification phase to develop a functional system architecture, which through decomposition will describe the overall system as a whole, the sub-systems, and the individual functions of the sub-systems. This functional system decomposition gives a clear overview of the entire system and its functionalities, allowing for a functional evaluation of the functional requirements.

### 3.1.3 Realisation Phase

The goal of the realisation phase is to actually build the envisioned product. The starting point of this phase is the functional system architecture from the specification phase, where each function was described. Now, each sub-system needs to be made, where a component is realised such that it performs the desired function. Each sub-system is realised, and then integrated together to form the prototype of the system as a whole. The components are selected based on the functions that need to be performed.

### 3.1.4 Evaluation phase

Finally, the CTDP concludes with a user evaluation phase. However, this graduation project focuses on the development of a technical solution; hence, this phase is focused on the functional testing of the system. The prototype is then evaluated, to check whether it meets the specific functional requirements that were finalised in the previous phase; if necessary, the prototype can then be altered and evaluated again such that the specific functional requirements are met.

## 3.2 Stakeholder Identification and Analysis

Stakeholder identification and analysis are important in order to manage the needs and expectations that each stakeholder has on the project. The theory of Mendelow [28] suggests that each stakeholder is analysed and categorised based on their power and interest of the project. In this theory, power is defined as the ability to influence the project, and interest is defined as how interested the are in the success of the project. Mendelow states, that a stakeholder that has high power and high interest over the project should be managed closely, and should be constantly informed about the decision progress of the project, and included in the decision making process. A stakeholder with high interest but low power over the project should be kept informed about the progress of the project, with minimal effort spent on including them in the decision making. A stakeholder with high power but low interest should be kept satisfied, as most likely they have spent significant resources on the project. A stakeholder with low power and low interest should be monitored, checking if their levels of interest or power change throughout the project.

## 3.3 Requirements Elicitation and categorisation

When working on a project, it is important to understand the specific requirements. These requirements come from different stakeholders, each stakeholder has different expectations and therefore different requirements. These requirements need to be categorised, both based on the expectation of the stakeholder, and on their importance to the project.

### 3.3.1 Interviews

In order to understand the specific stakeholder needs and requirements of the project, semi-structured and unstructured qualitative interviews were conducted. These type of interviews are flexible, and more conversational as opposed to a structured interview [29]. Unstructured interviews allow for a discussion of the design features and them to give input into the design process. Semi-structured interviews, consist of a set of some questions and topics previously prepared by the interviewer to be answered by the interviewee, but allow for additional questions and remarks to be made, in cases where some things need clarification or expansion. The semi-structured interviews are especially useful at understanding the interviewees' perspective and expectations of the project, and these are used to understand the specific requirements that a specific stakeholder has.

### 3.3.2 MoSCoW

Once the specific stakeholder requirements are collected and understood, they need to be categorised in order of priority. Throughout the development of a product, it could happen that not all of the requirements can be met due to technical or time constraints. Therefore, it is important to categorise those requirements that are most important both for the stakeholders, and the functionality of the final product. MoSCoW is a categorisation technique that helps manage priorities of the requirements, and consists of four categories namely, *Must Have, Should Have, Could Have, Won't Have* [30]. The *Must Have* category, is the highest priority, and these are the requirements which are guaranteed to be met by the developer of a product. The *Should Have* category is the second highest priority, and these are the requirements that are important, but not vital to the project. While it may be detrimental to the project if these requirements are left out, the final outcome is still viable. The *Could Have* category is the next order of importance, and it consists of requirements that are desirable, but not that important. If these requirements are left out, little to no impact would be made on the final product. The *Could Have* requirements would be delivered in the best case scenario, and little time and focus should be spent on them. Finally, the *Won't Have* category consists of requirements that have been agreed on that will not be delivered as a part of this timeframe of the project. These requirements are included in the categorisation list in order to manage expectations, and clarify the scope of the project. These requirements could be possible future works or developments of the final product, but not in the scope of this project.

## 3.4 Concept Ideation

In order to generate relevant concepts, it is important to utilise multiple concept generation techniques. This section describes brainstorming, however interviews and state of the art research also served as a means for concept generation in this graduation project.

### 3.4.1 Brainstorming

Brainstorming is a group problem solving methods that involves group members interacting with each other by sharing different ideas through a discussion. During brainstorming, group members are free to share any idea they have, and it is important to not criticise or put down any ideas during the brainstorming session [31]. This freedom to share any idea that comes to mind yields a large amount of ideas and concepts, where features from multiple ideas can be combined, or otherwise disregarded after the brainstorm session has finished. Next to group brainstorming, this project also made use of individual brainstorming, which allows an individual to come up with multiple ideas. Individual brainstorming benefits from the fact that one is less likely to go off topic than in a group session, and allows for a more focused ideation.

## 3.5 Product Specification

In order to describe the specification of a systems functionality, the entire system can be decomposed into its individual functions to develop a functional system architecture. Block diagrams of 3 levels of abstraction are used to visualise the system as a whole, the individual sub-systems, and finally the functions withing each sub-system. The starting point is level 0, which is an abstract overview of the functionality of the system as a whole. The next level, level 1, decomposes the entire system into its individual sub-systems, which gives a less abstract overview of the interactions of the system as a whole. The final level 2, decomposes each sub-system into each individual function. The final level is the least abstract, as it specifically describes how each sub-system interact with each other and the environment. See figure 8 for a graphical explanation of the level approach.

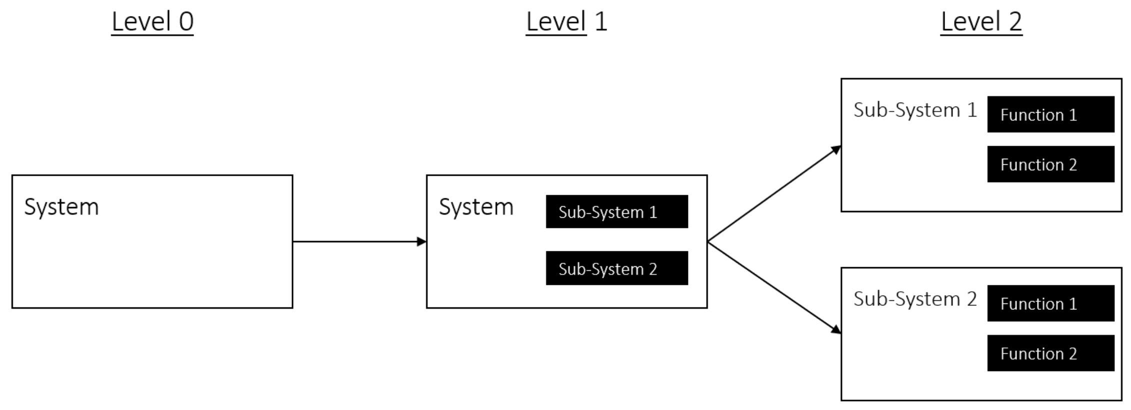


*Figure 8: Level approach functional decomposition*

# Chapter 4 – Ideation

This chapter describes the ideation phase of this project. The design question is the starting point of this phase, which in the context of this project is the research question defined in the first chapter. This chapter starts by presenting the identified stakeholders, followed by an analysis of their interest and involvement in this project. Next, the stakeholder needs that are based on the background research and stakeholder analysis. The remainder of the chapter presents four concepts of the turbidity measurement system which were developed during this project.

## 4.1 Stakeholder Identification and Analysis

Table 1 shows the identified stakeholders, with their role, motivators, and contact person. Figure 9 shows the power-interest matrix based on the theory of Mendelow (see chapter 3.2).

| Stakeholder | Role | Motivator(s) | Contact |
|---|---|---|---|
| NX-Filtration | Client, Primary user, Developer, Decision maker | -Dealing with water filtration<br>-Looking for alternative methods for water quality analysis<br>-Co-Sponsor of SRB35k | Mark Leijdekkers, Joris de Grooth |
| University of Twente | Secondary end user, Advisor | -Make use of the treated rainwater<br>-Owner of SRB35k | Richard Bults, Erik Faber |

*Table 1: Stakeholder Identification*

The key stakeholders in this project are NX-Filtration and the University of Twente [32]. NX-Filtration is the primary stakeholder as the correct working of their nanofiltration membrane technology that will be used to treat the collected and stored rainwater in the SRB35k will need to be monitored.

The University of Twente is a secondary stakeholder. Their interest is to use the treated rainwater for watering the trees and plants on its campus, and potentially for cleaning purposes.

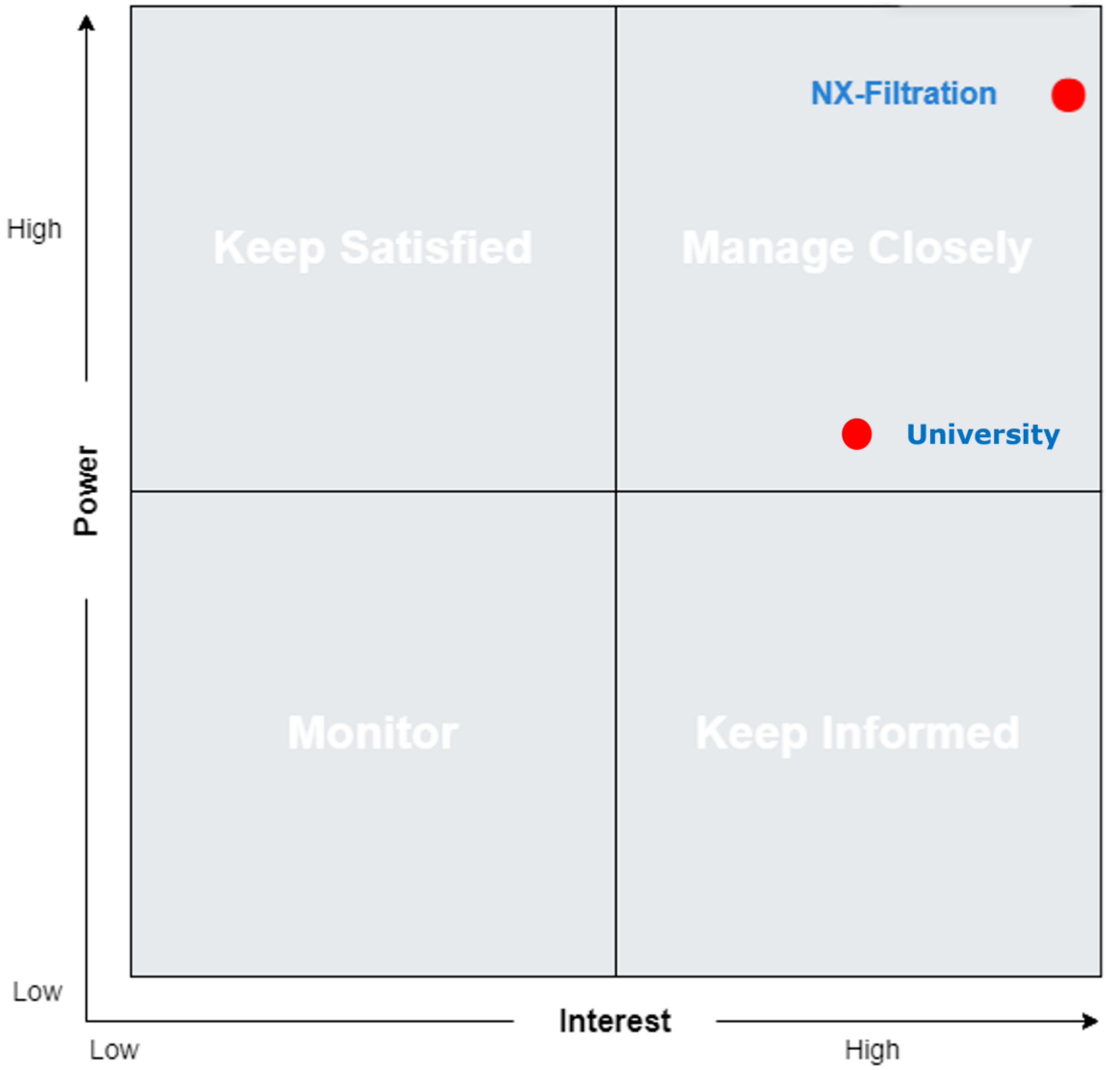


*Figure 9: Power-Interest matrix based on theory of Mendelow*

The stakeholder identification and power-interest matrix show that NX-Filtration has a high interest in this project. NX-Filtration is a co-sponsor of the SRB35k, and their filters will be monitored by the envisioned system. Their interest in this project stems from the fact that the current industry standard technologies that they use to monitor their filtration systems are expensive. They seek an alternative, cost-effective solution to monitor their filtration system, and therefore NX-Filtration are also the most powerful stakeholder in this project, as the specific requirements of the monitoring system need to match their standards. Therefore, according to the theory of Mendelow (see chapter 3.2) it is important to keep NX-Filtration satisfied, and they need to be fully informed and engaged in the decision-making process as they have the highest influence over this project.

The University of Twente also has a high interest in the development of this project, as ultimately the monitoring system will be installed on the SRB35k which is located on the university campus, making them the secondary end user of the system. However, the university has neutral power over this project, as the goal is to develop a proof of concept for a monitoring system of the filtration system. For those reasons, it is important to keep the university partly engaged and fully informed about the decision making and progress of the project. The university will play a key role in relations management with the client, and advice.

## 4.2 Stakeholder needs

In order to get insight into the specific requirements of the final product, numerous interviews were held with the stakeholders to understand their needs and expectations. As all the interviews were semi-structured, it allowed them to also serve as brainstorming sessions.

### 4.2.1 NX-Filtration

As discussed in the analysis of the identified stakeholders, the client, NX-Filtration is the most influential and important stakeholder in this project. It is vital for the development of the final product to understand their requirements that they have for the product, therefore multiple interview/brainstorm sessions were held with NX-Filtrations R&D team, Joris de Grooth and Mark Leijdekkers. During these meetings, their expectations for the project were discussed, along with preliminary requirements for the system.

After the first meeting, the scope of the project became clear. They don’t expect a fully working system ready to be installed on the SRB35k. Rather a comprehensive proof-of-concept on the feasibility of designing a low-cost turbidity measurement system. They want to see if it is possible to reduce the cost of their entire filtration process, which is currently limited by the high cost and limited availability of industry standard systems for water quality analysis. Therefore, the first and most important requirement is that the final system needs to be low cost (under 100 euro), featuring off the shelf components in order to make the reproducibility of the system feasible.

Another point that was discussed, is what must the system measure. NX-Filtration specialise in direct nanofiltration technology, meaning that their filters focus on filtering out nano particles. In order to monitor the correct working of their filtration system, the concentration of those nano particles need to be determined. This is due to the fact that if the filters start to underperform, the concentration of the nano particles will increase. Therefore, the system needs to be able to measure the concentration of nano particles.

Furthermore, the accuracy of the system was discussed. NX-Filtration are not interested in knowing the exact turbidity of the water, but rather to be able to reliably tell the difference between the permeate, and the concentrate. The envisioned system should be able to differentiate between the purified product water after passing through the filtration membrane (permeate), and the contaminated water that has not passed the filtration membrane (concentrate). In addition, the system should be able to measure the turbidity of both coloured, and colourless samples of water.

Table 2 shows the needs and expectation of NX-Filtration gathered from these interviews. The requirements are prioritised following the MoSCoW method described in chapter 3.3.2.

| Needs and expectations of NX-Filtration | |
|---|---|
| Must | |
| The system must be low cost. | 1 |
| The system must be able to measure turbidity of water caused by suspended nano particles. | 2 |
| The system must utilise infrared light of a selected 860nm wavelength | 2a |

| | |
|---|---|
| The system must be able to differentiate between the permeate and concentrate. | 3 |
| Should | |
| The system should be able to work with coloured and colourless water. | 4 |

*Table 2: NX-Filtration needs and expectations*

### 4.2.2 University of Twente

From multiple interviews and brainstorming sessions with two representatives of the university, Richard Bults and Erik Faber it became clear that they expect a proof-of-concept of low-cost system that can measure water quality. If the proof-of-concept is a success, they intend to continue the development of the system in future years. Therefore, the system should be designed in such a way that allows for further development in the future. The system should be simple and reproducible, such that the next person working on the system in the future can seamlessly take over. In addition, they expressed their interest in the system to allow for a modular design, such that it can be expanded to measure other parameters of water than turbidity.

Table 3 shows the needs and expectations of The University of Twente, based on the interviews and brainstorm sessions. The requirements are prioritised following the MoSCoW method described in chapter 3.3.2.

| Needs and expectations of The University of Twente | |
|---|---|
| Must | |
| Proof-of-concept of a low-cost system that can measure water quality | 1 |
| The system must be low cost. | 2 |
| Should | |
| The system should be simple | 3 |
| The system should be reproducible | 4 |

| | |
|---|---|
| The system should allow future development | 5 |
| The system should be modular | 6 |

*Table 3: Needs and expectations of The University of Twente*

## 4.3 Preliminary Concepts

Based on the stakeholder needs and expectations gathered during the interviews and brainstorm sessions, 4 concepts for a low-cost turbidity measurement system were created. The first concept is inspired by the design of Huzaifa Nayeem et al [9] as described in chapter 2.2. Every next concept is an evolution of the previous one, based on the evaluation of the results from the rigorous testing described in chapter 6.3.

### 4.3.1 Concept 1 – White

Displayed in figure 10 is the first concept of the system. It features a white casing, which is placed around a transparent water pipe, along with slots for the light source and detectors. The goal of this concept is to analyse the effect of turbidity on the amount of scattering. Using a white casing for the first concept serves as the starting point. It features two slots for the light detector, one being placed at a 90° angle for nephelometric measurements, and one directly in front of the light source, to allow for possible future turbidimetric measurements. There are three slots for the light source, this was done intentionally, in order to allow for different light sources of different wavelengths to be used for measuring different parameters of water quality in the future.

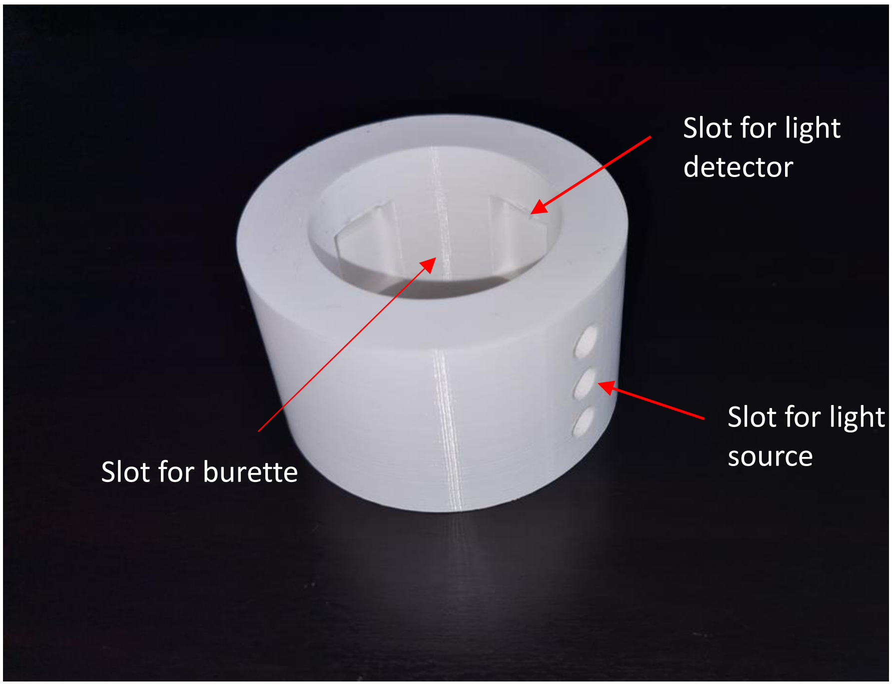


*Figure 10: Concept 1 - White*

### 4.3.2 Concept 2 – Black

Shown in figure 11 is the second concept of the system. This concept is an evolution of concept 1, with the difference being only in the colour of the casing which is now black. The goal for this concept was to analyse the effect that a black casing has on the accuracy and reliability of the readings. The reasoning for the black material is two-fold, firstly, black material isolates better from ambient light, and absorbs infrared light, as opposed to reflecting it like in the case of the white casing.

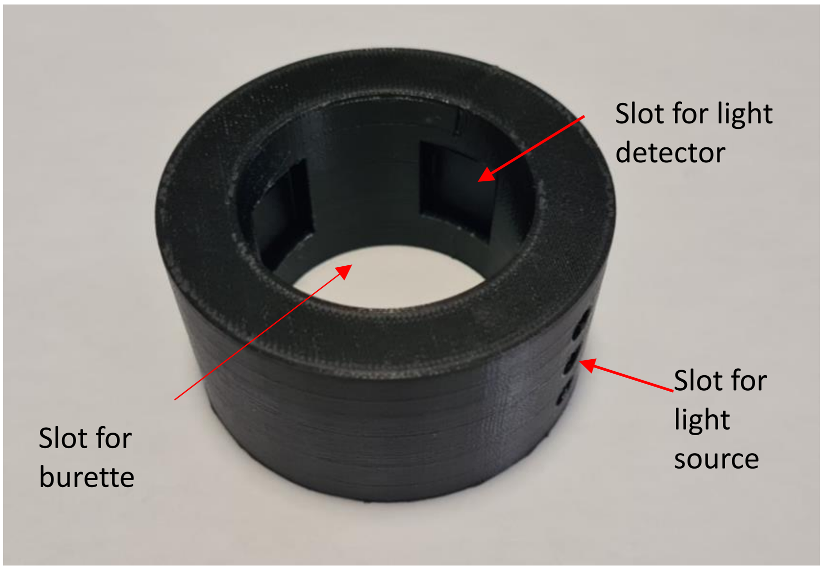


*Figure 11: Concept 2 - Black*

### 4.3.3 Concept 3 – Narrow light source

Shown in figure 12 is the third concept of the system. This concept is an evolution of concept 2 and features a black casing which is placed around a transparent burette. The key difference in the design of this concept is the narrow opening for the light source. The aim of the third concept is to minimise the light beam angle, such that it is narrower and more direct. The goal is to analyse the effect of a narrow light beam angle on the accuracy of the readings.

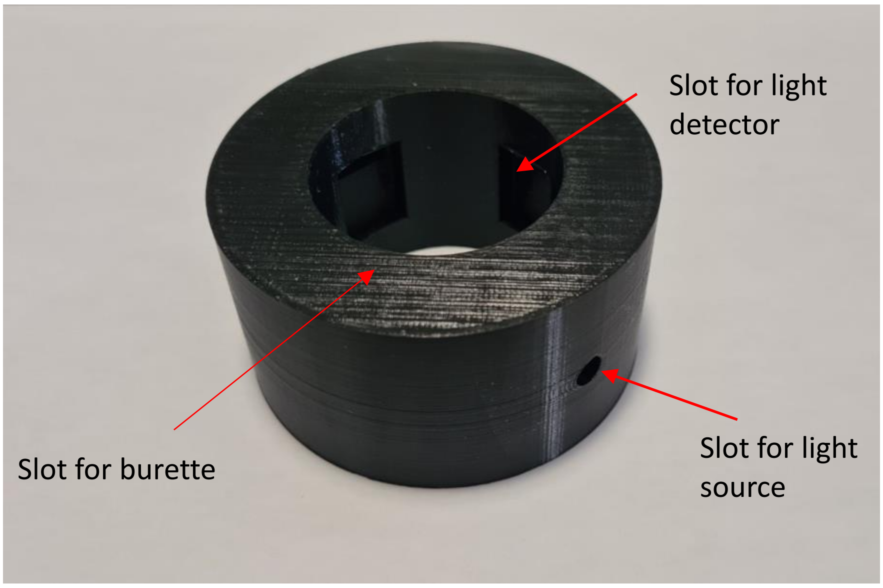


*Figure 12: Concept 3 - Narrow light source*

### 4.3.4 Concept 4 – Cuvette design

Shown in figure 13 is the fourth and final concept of the system. This concept differs to the previous three in one key distinct way, as opposed to it being placed around a transparent burette, it has a slot in the middle in which a cuvette is inserted. This concept features a black casing using equal material to concept 2 and 3, and slots for the light source and detector equal to concept 2.

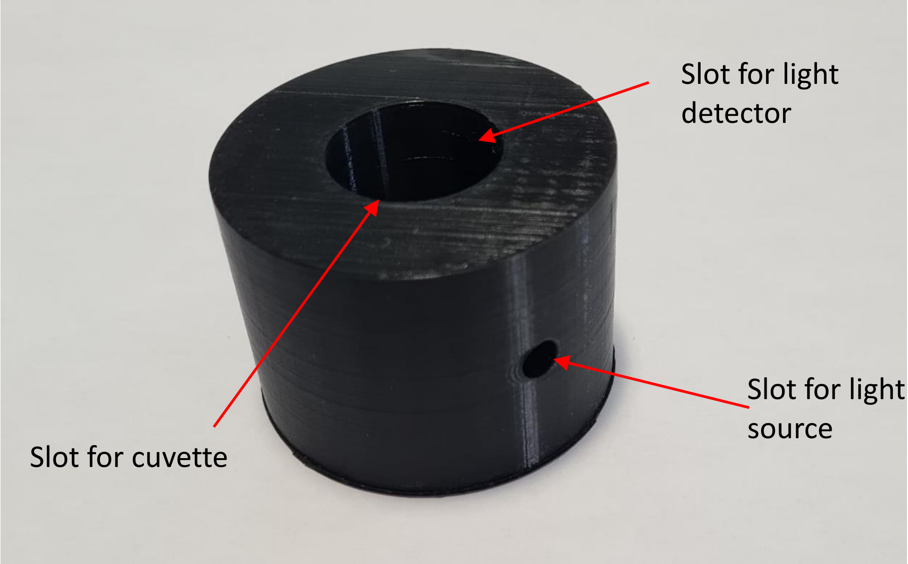


*Figure 13: Concept 4 - Cuvette design*

# Chapter 5 – Specification

This chapter describes the specification phase of the project. The specification phase builds upon the ideation phase, where four concepts were presented, and the preliminary stakeholder requirements were defined. Each concept has been developed in the realisation phase; therefore, each concept is specified. That being said, all four concepts share the same functional architecture, as the next concept is an evolution of the previous. Thus, this chapter first presents the functional architecture of the turbidity measurement system, followed by a specification of each concept. This chapter concludes with presenting the evaluated functional and non-functional requirements of the system.

## 5.1 Functional Architecture

This section presents the functional architecture of the turbidity measurement system decomposed to 3 levels, starting with an overview of the system. Next, the functions are decomposed, and the combined functions are presented. This section concludes with the final decomposition where the specific individual functions of the system are described.

### 5.1.1 Level 0 Decomposition: System overview

Shown in figure 14, is a black-box overview of the nano particle turbidity measurement system. As can be seen in the diagram, the turbidity measurement system has one output, the incident infrared 860nm light that passes through the water sample. Following the preliminary requirements presented in chapter 4.2.1, NX-Filtration are interested in measuring the concentration of nanoparticles. Therefore, nephelometry will be applied. The system also has one input, the light that has been scattered by the suspended nanoparticles.

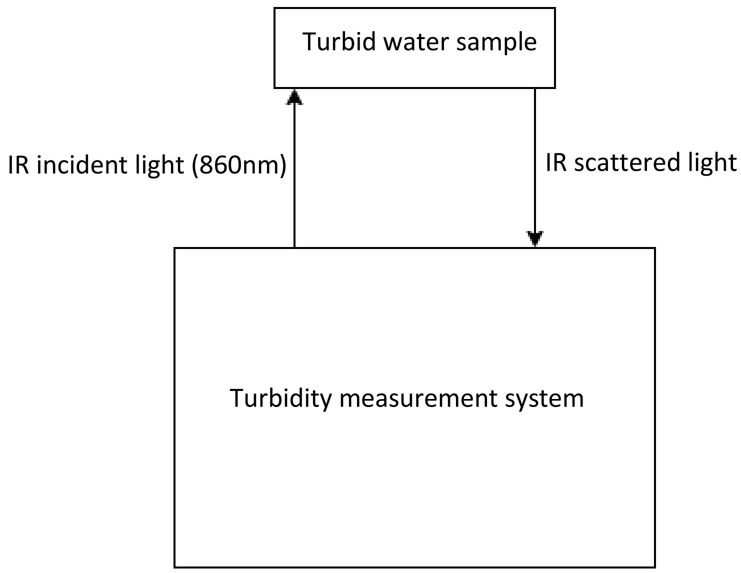


*Figure 14: Overview of the Nano Particle Turbidity Measurement System*

### 5.1.2 Level 1 Decomposition: Combined functions

Shown in figure 15 is the first level of decomposition of the system into its main functions: the IR light emitter, and IR light receiver. The IR light emitter generates the infrared 860nm light source, this is the source of the incident light that passes through the water sample. The IR light receiver is responsible for measuring the intensity of the light that was scattered by the suspended nanoparticles in the water sample.

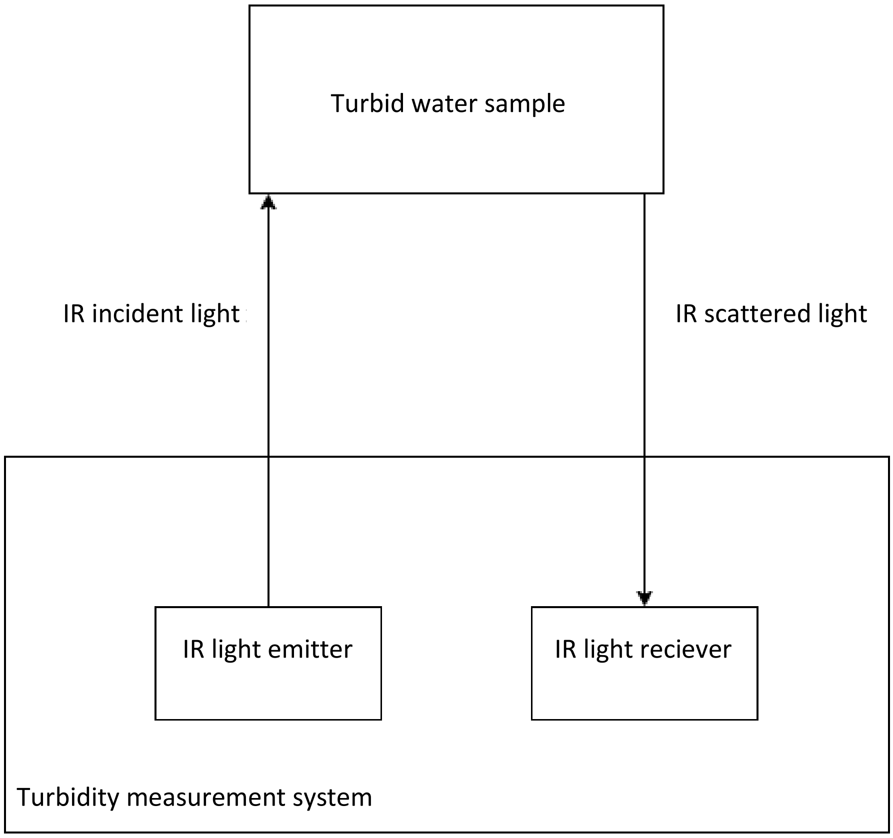


*Figure 15: Decomposition of Turbidity Measurement System*

**IR light emitter**

One of the requirement of NX-Filtration presented in chapter 4.2.1 is that the turbidity measurement system should be compatible with both coloured and colourless water samples. Therefore, an infrared light source is used, as described in chapter 2.1.3 this allows for both coloured and colourless samples of water to be measured. More specifically, a wavelength of 860nm has been chosen, as this is the same wavelength that the industry standard Lovibond TB 211IR uses, allowing for a fair comparison between the two systems. In order to minimise the interference of other wavelengths ideally, the light source would only emit light of a wavelength of 860nm with a full width at half maximum (FWHM) approaching 0; but as that is not possible, a narrowband light source is used, meaning that a narrow range of wavelengths are emitted, peaking at 860nm, with a FWHM of 30nm.

**IR light receiver**

As the abovementioned incident light is infrared, the light that is scattered by the suspended nanoparticles is the same wavelength. Therefore, an infrared light detector is used, as the detector needs to be able to detect the intensity of the scattered infrared light. Specifically, the detector measures the intensity of light of an 860nm wavelength.

## 5.2 Specification of Concepts

Table 4 shows the specification of the four casing concepts that were developed.

| | Colour | Light source slot diameter | Slot for burette/cuvette diameter | Water sample storage |
|---|---|---|---|---|
| Concept 1 – White | White | 6mm | 42.9mm | Burette |
| Concept 2 – Black | Black | 6mm | 42.9mm | Burette |
| Concept 3 – Narrow light source | Black | 2mm | 42.9mm | Burette |
| Concept 4 – Cuvette design | Black | 6mm | 24.5mm | Burette |

*Table 4: Specification of Concepts*

The design of the concept 4 (cuvette design) mimics the design of the industry standard Lovibond TB 211IR turbidity measurement system, as the exact same cuvette can be tested using both systems. This feature allows for a one-to-one comparison in the evaluation between the envisioned system and the industry standard.

## 5.3 Evaluated System Requirements

In conjunction with the preliminary stakeholder requirements (see chapter 4.2) and the decomposition of the functional architecture, table 5 shows the final functional and non-functional requirements for the turbidity measurement system.

| 5.2.1 Functional Requirements | 5.2.2 Non-functional Requirements |
|---|---|
| **Must** | |
| The system must be able to measure turbidity of water. | The system must be low cost. |
| The system must be able to differentiate between the permeate and concentrate. | The system must allow future development |
| The system must measure the concentration of suspended nano particles. | |
| **Should** | |
| The system should be compatible with coloured and colourless water. | The system should be simple |
| | The system should be reproducible |
| | The system should use off-the-shelf components. |
| **Could** | |
| | The system could be modular |

*Table 5: Final system requirements*

# Chapter 6 – Realisation

This chapter describes the realisation phase of the project. The starting point of this phase is the functional architecture of the four concepts, and the specification of each concept presented in chapter 5. This chapter starts off with a decomposition of the system into its individual components, where the reasoning behind each choice of component is explained. Next, the realisation of each of the four concept is presented, and described in detail. This chapter concludes with a description of the testing procedure for each of the concepts.

## 6.1 Decomposition of system

Based on the functional architecture presented in chapter 5.1, each of the four concepts can be decomposed into four distinct individual components.

- Infrared light source
- Infrared light detector
- Casing for the light source and light detector
- Water sample container

As each next concept is an evolution of the previous one, each concept features the exact same electrical components. This was done intentionally, in order to eliminate component spread between two same sensors, allowing a fair comparison between the different concepts.

### 6.1.1 Light Source

Figure 16 shows the emission spectrum of the *SFH 4554 AMS infrared LED (860nm)* [33].

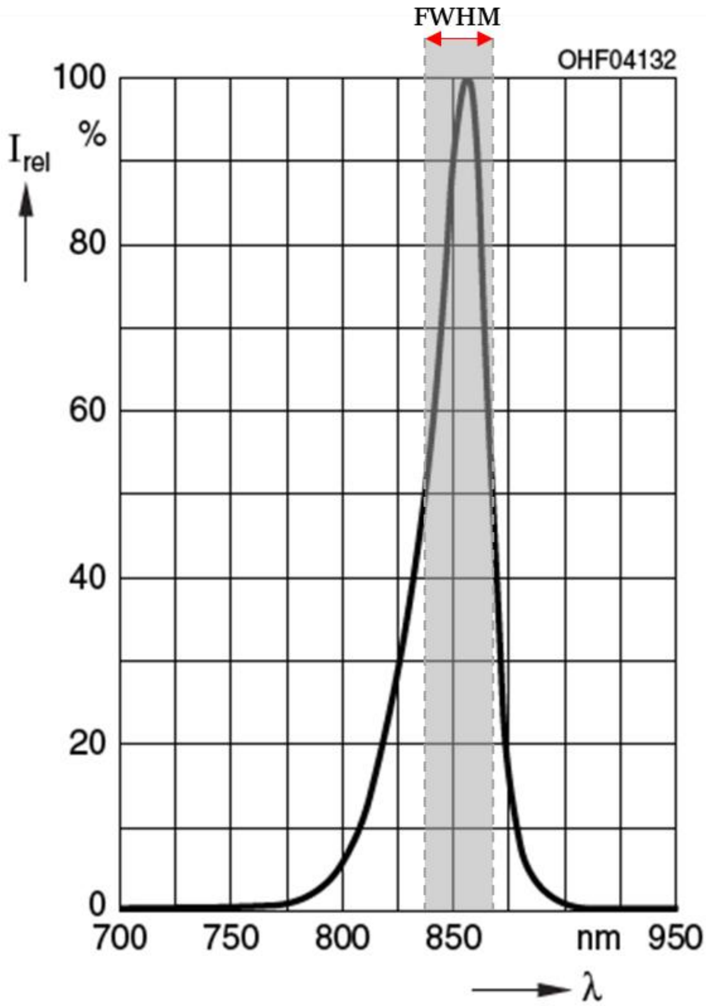


*Figure 16: SFH 4554 AMS infrared LED emission spectrum*

As specified in section 5.1.3, the infrared light source should be narrowband, peaking at a wavelength of 860nm. The graph of the emission spectrum of the LED, shows that both of these requirements are satisfied. The *SFH 4554 LED* is narrowband, which is given by the low Full Width at Half Maximum (FWHM). The FWHM is a measure of the spread of the emitted wavelengths of light; the smaller the FWHM, the more narrowband an LED is. From the datasheet of the LED [33], the FWHM is 30nm. In addition, the datasheet specifies that the peak wavelength of this LED is at 860nm. Therefore the *SFH 4554 Infrared LED* is chosen for this project.

### 6.1.2 Light Detector

Figure 17 shows the graph of the spectral responsivity of the TSL2561 digital light detector [34].

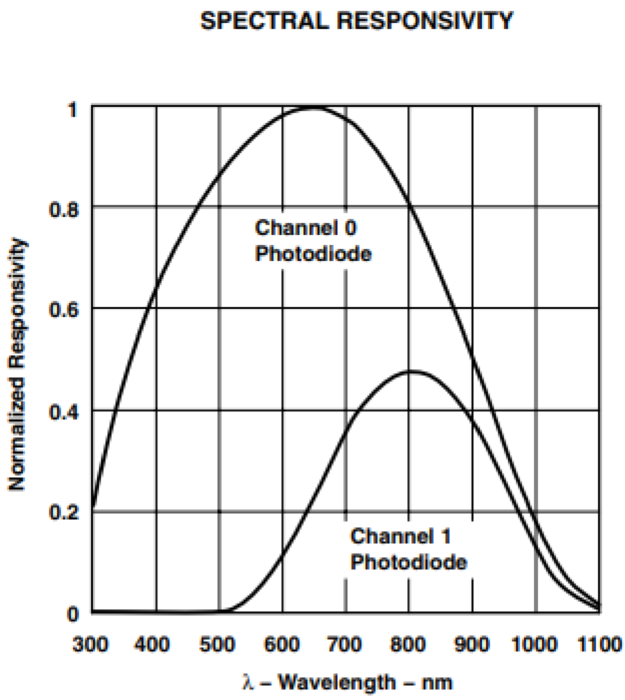


*Figure 17: Spectral Responsivity of the TSL2561*

As specified in section 5.1.3, the light detector needs to measure the intensity of infrared light, more specifically the intensity of the scattered light at a wavelength of 860nm. The above graph is from the datasheet of the sensor, and it shows the spectral responsivity of the TSL2561 digital light detector. This digital light detector consists of two channels. Channel 0 that can detect the intensity of a wide spectrum, ranging from near ultraviolet, to infrared. This channel encompasses a wide range of wavelengths, which could introduce error, as wavelengths that are not of interest would also be measured. That being said, channel 1 specifically measures the intensity of infrared light, with the spectral responsivity peaking at just over 800nm. This means that shorter and longer wavelengths will not have such a high on the measurement, as the detector is less sensitive to shorter and longer wavelengths; meaning that there will be less interference from ambient light. Due to these facts, the TSL2561 is chosen as the light detector for the system.

### 6.1.3 Casing

As specified in section 5.1.1, the system will apply nephelometry, in order to measure the concentration of suspended nanoparticles. As described in section 2.1.4, a nephelometric measurement method consists of a light detector arranged at 90° to the light source, in order to measure the intensity of scattered light by the suspended nanoparticles. Therefore, the casing is designed in such a way, that it ensures a perfect perpendicular alignment between the *SFH 4554 Infrared LED*, and the *TSL2561 digital light detector.* While each concept comes with a change to match the design features of the casing, the arrangement of the two components remained unchanged.

### 6.1.4 Water sample container

In order to measure the turbidity of a water sample, the water sample needs to be stored in a container. That container needs to be transparent, such that it does not absorb, reflect, or otherwise interfere with both the incident, nor scattered light. Two different water sample containers were used, depending on what concept was being tested. Namely, a transparent glass burette (see figure 18), and a quartz crystal cuvette (see figure 19). The reasoning behind using a transparent glass burette, was to replicate the experimental setup described by Nayeem et. al in their paper *Towards Development of a Simple Technique based Wavelength Specific Absorption for Quality Measurement of Flowing Water* [9], (see section 2.2.2). The quartz crystal cuvette was used for the final concept, as the same quartz crystal cuvette was used by the industry standard Lovibond TB 211IR[23], allowing for a one-to-one comparison between the two systems.

*Figure 18: Glass burette*

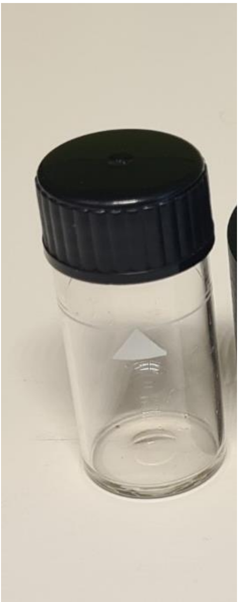

*Figure 19: Quartz crystal cuvette*

## 6.2 System Description

This section contains the description of the realisation of each of the four concepts. Based on the previously conducted research, and the specified system requirements, four concepts were developed, and tested.

### 6.2.1 Concept 1 – White casing

The goal of the first prototype was to analyse what effect do different turbidity water samples have on the amount of light being scattered. Concept 1 features a white casing which was 3D printed using an Ultimaker 3 3D printer using a 2.85mm filament diameter, with the internal diameter of the ring being 42mm ensuring a tight fit around the burette, along with a 6mm light source opening.

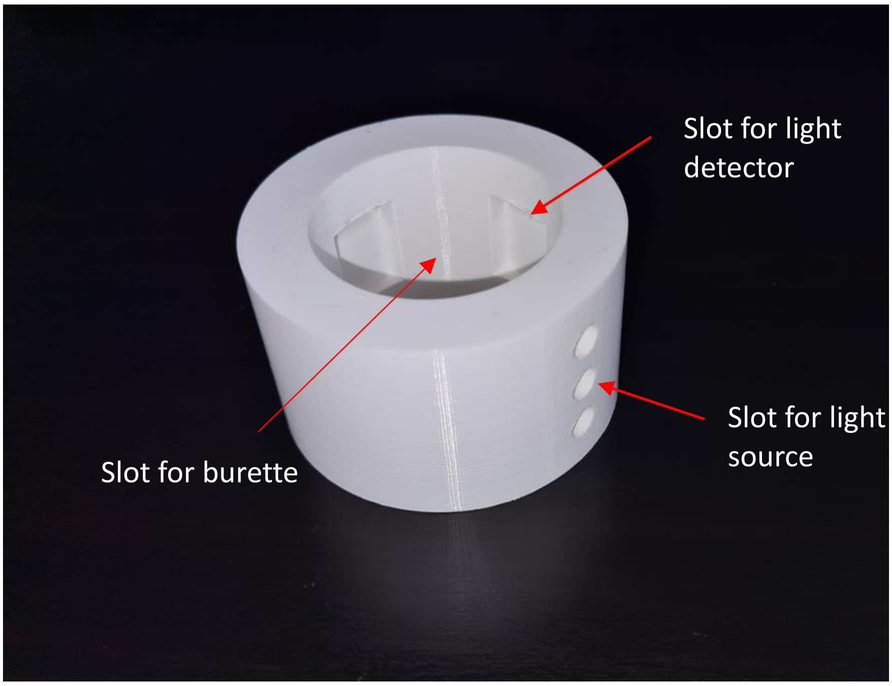


*Figure 20: Concept 1 - White Casing*

*Figure 21: Concept 1 on burette*

### 6.2.2 Concept 2 – Black casing

The goal of the 2nd prototype was to minimise the internal scattering of light. Concept 2 is the exact same model as the previous concept, 3D printed using the same printer and specs as concept 1, this time however using black filament as opposed to white. The reason for this is that black material absorbs infrared light, as opposed to reflecting it.

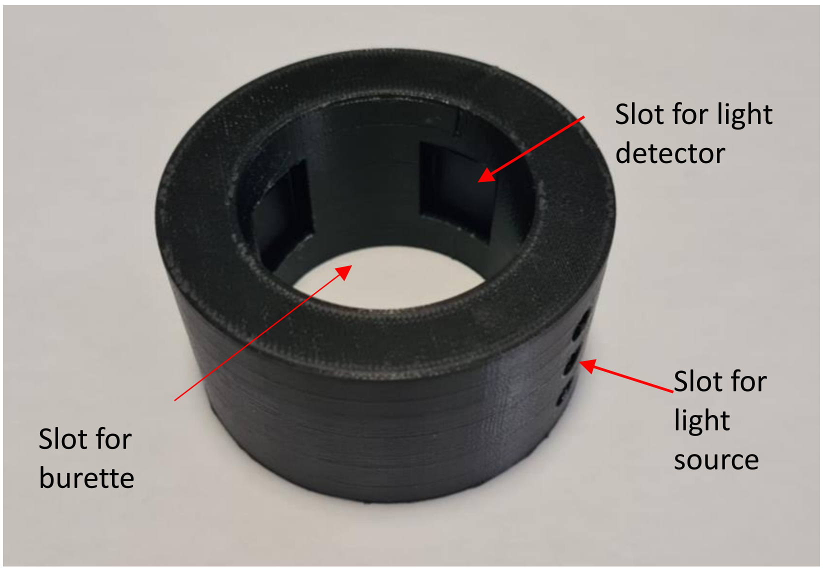


*Figure 22: Concept 2 - Black Casing*

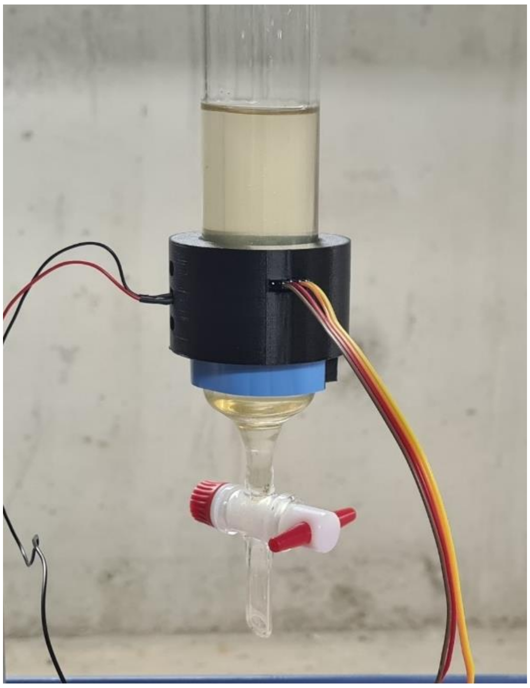

*Figure 23: Concept 2 on burette*

### 6.2.3 Concept 3 – Narrow light source

The goal of the 3rd prototype was to analyse the effect a smaller light source opening has on the readings. Concept 3 features a Black 3D printed casing, same internal diameter as previous concepts, but this time the opening for the light source is reduced on the inside to 2mm. The reason for this is to minimise the amount of light that can shine directly onto the detector, as opposed to being scattered by the suspended particles.

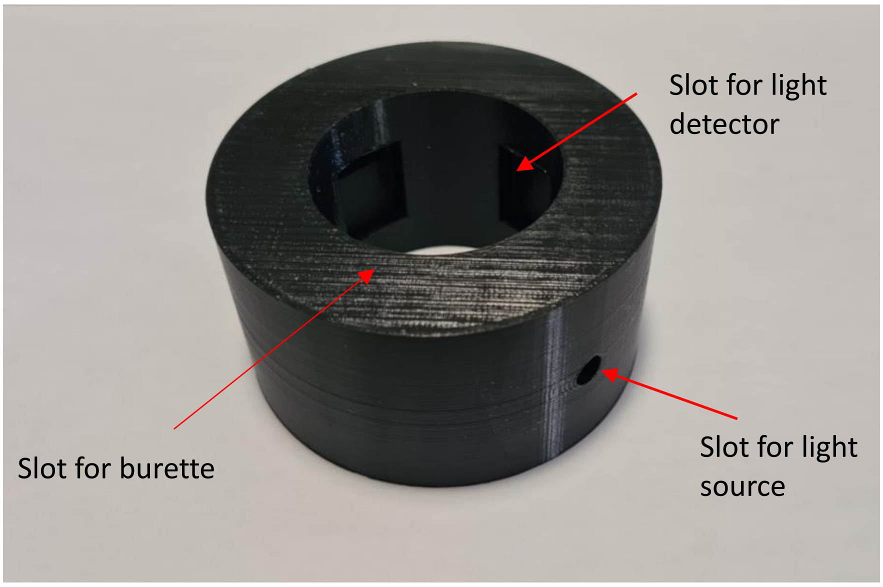

*Figure 24: Concept 3 - Narrow Light Source*


*Figure 25: Concept 3 on burette*

### 6.2.4 Concept 4 – Cuvette design

The goal of the final concept was to accurately measure the turbidity of an unknown sample of water. The final concept features a black 3D printed casing, along with a 6mm light source opening, and a 24mm inner diameter which fits the quartz crystal cuvette as opposed to a burette. The reasoning behind this change is that now the exact same sample can be tested with the final concept, and with the industry standard Lovibond TB 211IR, allowing for a fair comparison between the two systems.

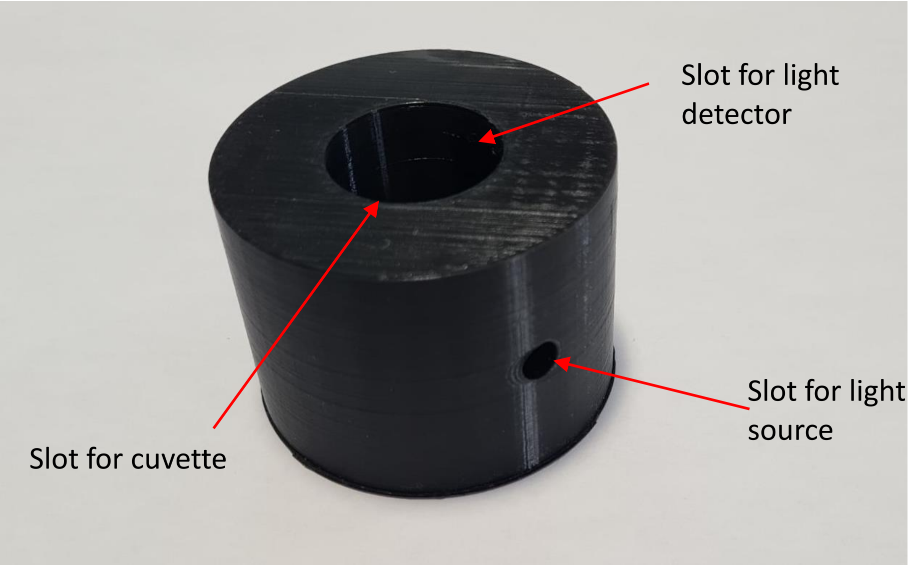

*Figure 26: Concept 4 - Final Concept*


*Figure 27: Concept 4 with cuvette inserted*

### 6.3.3 Concept 4 Calibration Procedure

In order to transform the raw data into NTU, concept 4 was calibrated using three sealed control samples of known turbidity that come in the box with the Lovibond TB 211IR, namely 0 NTU, 20 NTU, and 200 NTU.


*Figure 28: Control samples of known turbidity used for calibration*

Each of the cuvettes were inserted into the casing, and the scattering intensity for each sample was recorded for 60 seconds, in order to get a large dataset to eliminate any abnormalities in the readings and outliers. The average of the scattering intensity per sample was taken, and plotted against the known NTU of the sample.

| **Concept 4 Calibration** | | | |
|---|---|---|---|
| **NTU (Control Sample)** | 0 | 20 | 200 |
| **IR Scattering Intensity (Average)** | **72.127551** | **122.433673** | **512.989796** |
| **STDEV IR (Dataset)** | **0.3628911** | **0.412727956** | **0.46299439** |

*Table 6: Concept 4 Calibration Data*

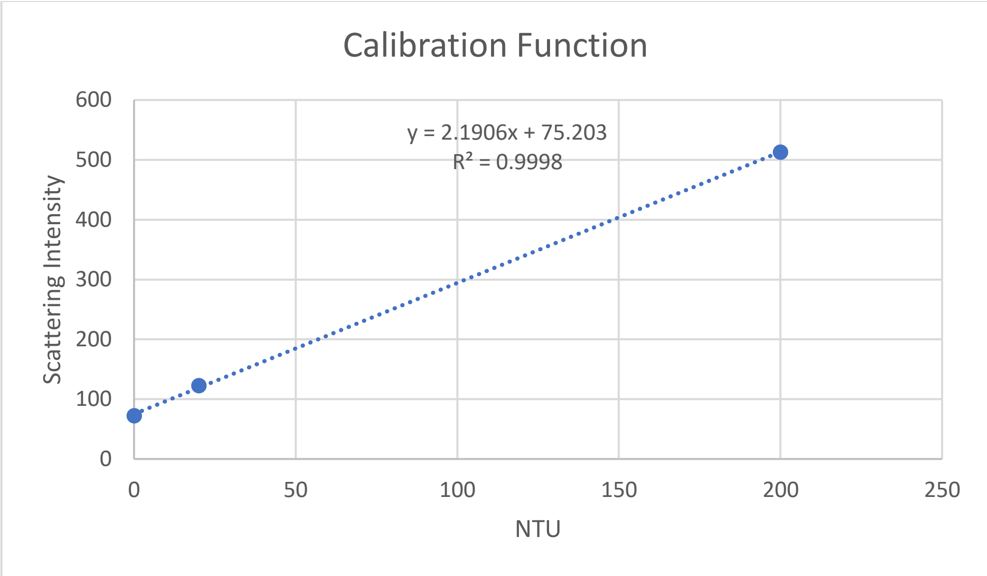


*Figure 29: Calibration Curve of Concept 4*

The linear line of regression gives the calibration function. The equation of the calibration function when rearranged for X Gives the equation for the nephelometric turbidity units for the final system.

$$NTU = \frac{SI - 75.203}{2.1906}$$

*Equation 1: Nephelometric Turbidity Unit Equation for Concept 4*

NTU = Nephelometric Turbidity Units
SI = Scattering Intensity

For each sample tested, the scattering intensity was inserted into the equation, thus determining the turbidity in terms of NTU of each sample.

# Chapter 7 – Evaluation

This chapter presents the evaluation of the four concepts developed. This chapter starts with showing the raw data, followed by an analysis and interpretation of that raw data. This chapter is concluded with an evaluation of the interpreted data and of each concept.

## 7.1 Functional System Testing Procedure

### 7.1.1 Testing Procedure Concepts 1-3

This section describes the testing procedure for concepts 1, 2, and 3. Each of the three concepts were tested using the following method:

- In order to limit the amount of ambient light which causes interference, all tests were conducted in a pitch black environment, namely in a basement.
- The Infrared LED and the digital photodetector were inserted into their designated slots in the casing, and connected to a microcontroller (Arduino Uno), see appendix 1 for the source code.
- A glass burette was thoroughly cleaned, by passing clean water through it multiple times, and attached to a clamp stand, such that its position is securely fixed (see figure 18).
- The casing along with the components was then placed around the burette and secured in place near the bottom (see figure 21, 23, 25).
- Ensuring that there is no ambient light pollution, the system is ready to test.
- Each sample of water was tested with the industry standard Lovibond TB 211IR to determine its turbidity.
- For each prototype, 4 tests were conducted:
  - With a clean empty burette
  - Burette with Low turbidity water sample (1 NTU)
  - Burette with Medium turbidity water sample (13.5 NTU)
  - Burette with High turbidity water sample (43 NTU)
- The entire 150ml water sample was poured into the closed burette, and the intensity of the scattered infrared light was recorded for 60 seconds,

in order to get a large dataset to eliminate interference from any abnormalities in the readings and outliers.

### 7.1.2 Testing Procedure Concept 4

This section describes the testing procedure of concept 4.

- Same as with the previously described method, all measurements were performed in pitch black in order to minimise the interference of ambient light.
- The Infrared LED and the digital photodetector were inserted into their designated slots in the casing, and connected to a microcontroller (Arduino Uno), see appendix 1 for the source code.
- A 10 ml quartz crystal cuvette (see figure 19) was cleaned, by rinsing it multiple times with clean water.
- The quartz crystal cuvette was filled with a sample of water of unknown turbidity, which was previously prepared by NX-Filtration, and inserted into the casing. The intensity of the scattered light was measured and recorded for 60 seconds in order to get a large dataset to eliminate interference from any abnormalities in the readings and outliers.
- That same cuvette filled with the same sample was then inserted into the industry standard Lovibond TB 211 IR to determine its turbidity, and to allow a fair comparison between the industry standard, and the low cost concept 4.
- This process was repeated for 6 different samples, all of which were previously prepared by NX-Filtration.

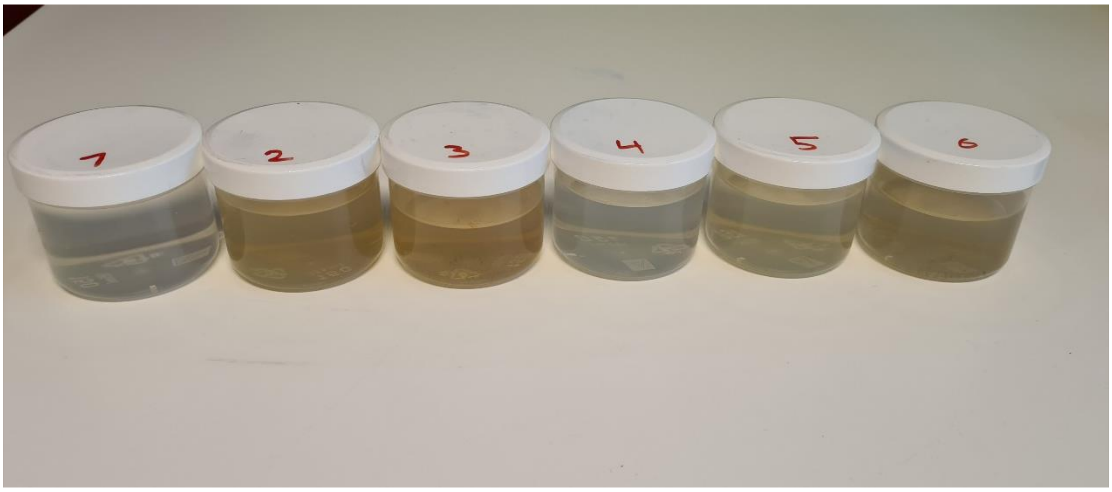


*Figure 30: Samples of turbid water prepared by NX-Filtration*

## 7.2 Raw data

In this section, the raw data gathered from the tests described in section 7.1 is presented. For each concept, the measurements were recorded for 60 seconds, at a frequency of around 3.25 Hz, or roughly every 0.3 seconds, which resulted in nearly 200 data points for each measurement. Due to the large amount of data, only the average of those 200 data points is presented. The full raw data can be found in appendix 2. The light detector used, TSL2561, not only measures infrared intensity, but also the full spectrum intensity, visible light intensity, and calculates the LUX (unit of measurement of light intensity). However, for these tests, only the infrared light intensity is of interest.

### 7.2.1 Concept 1 – White

| Concept 1 Average Measurements | | | | |
|---|---|---|---|---|
| | Empty Burette | 1 NTU | 13.5 NTU | 43 NTU |
| **IR (Scattering Intensity)** | 1980.62 | 1032.95 | 1075.05 | 1124.93 |
| **Full (Scattering Intensity)** | 2536.58 | 1308.64 | 1357.2 | 1423.60 |
| **Visible (Scattering Intensity)** | 555.96 | 275.69 | 282.16 | 298.67 |
| **Lux (Scattering Intensity)** | 8.99 | 4 | 4 | 4 |

*Table 7: Concept 1 Average Measurements*

### 7.2.2 Concept 2 – Black

| Concept 2 Average Measurements | | | | |
|---|---|---|---|---|
| | Empty Burette | 1 NTU | 13.5 NTU | 43 NTU |
| **IR Scattering Intensity)** | 60 | 12.64 | 20.60 | 77.5 |
| **Full Scattering Intensity)** | 81 | 16.74 | 27.08 | 103.13 |
| **Visible Scattering Intensity)** | 21 | 4.10 | 6.46 | 25.63 |
| **Lux Scattering Intensity)** | 0 | 0 | 0 | 0.79 |

*Table 8: Concept 2 Average Measurements*

### 7.2.3 Concept 3 – Narrow light source

| Concept 3 Average Measurements | | | | |
|---|---|---|---|---|
| | Empty Burette | 1 NTU | 13.5 NTU | 43 NTU |
| **IR Scattering Intensity)** | 28 | 4 | 5 | 15 |
| **Full Scattering Intensity)** | 36 | 6 | 7.04 | 20.44 |
| **Visible Scattering Intensity)** | 8 | 2 | 2.04 | 5.44 |
| **Lux Scattering Intensity)** | 0 | 0 | 0 | 0 |

*Table 9: Concept 3 Average Measurements*

### 7.2.4 Concept 4 – Cuvette design

| Concept 4 Average Measurements | | | | | | |
|---|---|---|---|---|---|---|
| | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 | Sample 6 |
| IR Scattering Intensity) | 76.3265 31 | 148.6428 57 | 144.0204 08 | 91.20918 37 | 97.24489 8 | 171.1326 53 |
| Full Scattering Intensity) | 99.5765 31 | 197.1530 61 | 191 | 120.2295 92 | 128.1989 8 | 225.8673 47 |
| Visible Scattering Intensity) | 23.25 | 48.51020 41 | 46.97959 18 | 29.02040 82 | 30.95408 16 | 54.73469 39 |
| Lux Scattering Intensity) | 0 | 1 | 1 | 1 | 1 | 1 |

*Table 10: Concept 4 Average Measurements*

## 7.3 Interpretation of raw data

### 7.3.1 Concept 1 – White

The goal of the first concept was to analyse what effect do different turbidity water samples have on the amount of light being scattered. Figure 31 shows the average infrared scattering intensity of each sample measured by concept 1, plotted against the actual turbidity of the sample measured using the Lovibond TB 211IR.

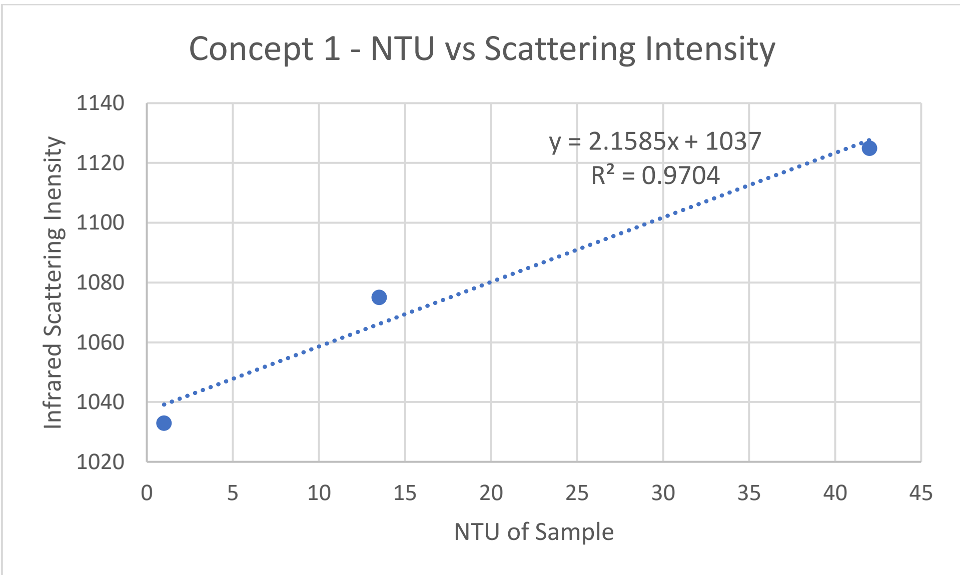


*Figure 31: Concept 1 - NTU vs Scattering Intensity*

After running the previously described tests, it was concluded that the amount of scattered light increases with high turbidity water samples, which follows the theory. That being said, concept 1 was subject to high internal scattering which was caused by the fact that infrared light was scattered by the white casing itself. This is shown by the fact that even for a low turbid water sample, there is high scattering present. This caused the readings to be inaccurate, and not reliable, shown by the relatively high average standard deviation of 1.65 and therefore necessitate the development of the next concept.

### 7.3.2 Concept 2 – Black

The goal of concept 2 was to minimise the internal scattering of light. Concept 2 is the exact same model as the previous concept, this time however printed in black as opposed to white. Figure 32 shows the average scattering intensity of each sample measured by concept 2, plotted against the actual turbidity of the sample measured using the Lovibond TB 211IR.

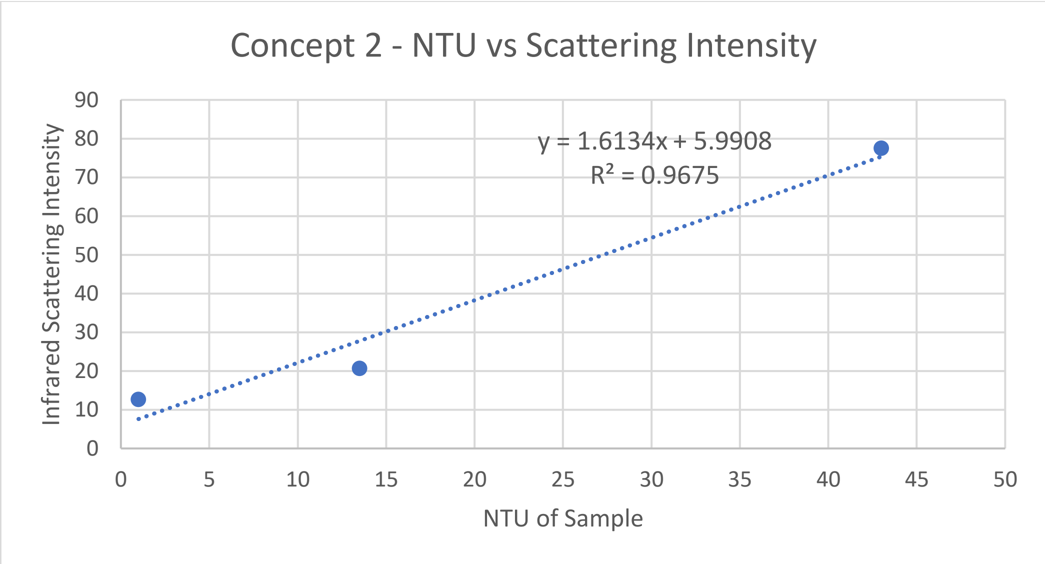


*Figure 32: Concept 2 - NTU vs Scattering Intensity*

This evolution of the design significantly reduced the internal scattering of light, which can be seen from the fact that the scattering intensity is orders of magnitude lower for each sample than in concept 1. In addition, for a sample of water of low turbidity, the scattering intensity is much closer to 0, compared to being over 1000 in concept 1. This significantly improves the accuracy and reliability, as the detector is now less subject to interference from the light scattered by the casing itself. Thanks to the increased reliability, the standard deviation of the dataset dropped, with the average standard deviation being 0.41. This meant that a positive linear relationship was observed, shown by the positive $R^2$ value of 0.967, between the intensity of scattered light, and the turbidity of the water sample, which is exactly what was expected.

The linear line of regression gives the calibration curve. The equation of the calibration curve when rearranged for X Gives the equation for the nephelometric turbidity units for concept 2, namely:

$$NTU = \frac{SI - 5.9908}{1.6134}$$

*Equation 2: Nephelometric Turbidity Units Equation for Concept 2*

NTU = Nephelometric Turbidity Units
SI = Scattering Intensity

### 7.3.3 Concept 3 – Narrow light source

The goal of concept 3 was to analyse the effect a smaller light source opening has on the readings. The reason for this is to minimise the amount of light that can shine directly from the light source onto the detector, as opposed to being scattered by the suspended particles, with the aim of improving accuracy and reliability. Figure 33 shows the scattering intensity of each sample measured by concept 3, plotted against the actual turbidity of the sample measured by the Lovibond TB 211IR.

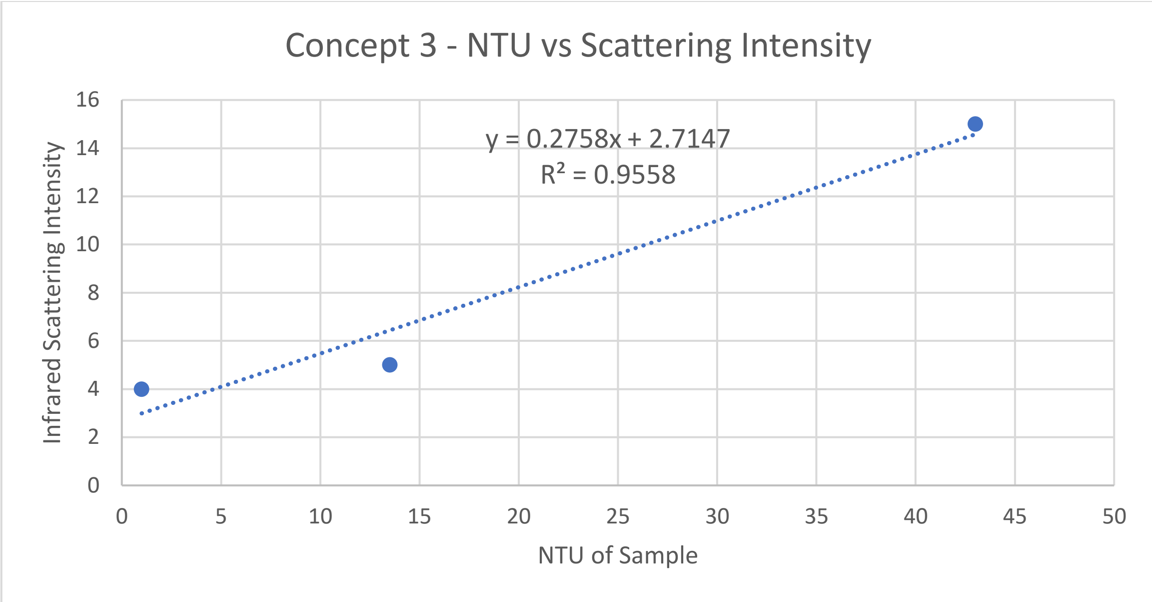


*Figure 33: Concept 3 - NTU vs Scattering Intensity*

The reduction of the diameter of the light source opening from 6mm to 2mm resulted in a reduction in sensitivity, where the difference between two samples of similar turbidity was not picked up by the system. This can be seen in the raw data (7.1.3) when comparing the scattering intensity of the 1 NTU sample and the 13.5 NTU sample, having an average scattering intensity of 4 and 5 respectively. In addition, this changed resulted in a reduced linearity of the line of best fit, where the $R^2$ value is the lowest of the previous 2 concepts, namely 0.9558.

The linear line of regression gives the calibration curve. The equation of the calibration curve when rearranged for X Gives the equation for the nephelometric turbidity units for concept 3, namely:

$$NTU = \frac{SI - 2.7147}{0.2758}$$

*Equation 3: Nephelometric Turbidity Units Equation for Concept 3*

NTU = Nephelometric Turbidity Units

SI = Scattering Intensity

## 7.4 Evaluation of results

### 7.4.1 Evaluation of Concept 1 – 3

Based on the testing and evaluation of the three prototypes, it was concluded that in order to ensure accuracy and high sensitivity, the needs to be printed in black in order to reduce the internal scattering, with a 6mm opening for the light source to increase sensitivity. The scattering intensity of 3 unknown samples of turbid water were measured using both concept 2 and concept 3 following the method described in chapter 7.1. Using the equation presented in section 7.3.2 and 7.3.3 respectively, the turbidity of the 3 unknown samples was predicted. In addition, each unknown water sample was tested using the industry standard Lovibond TB 211IR. Table 11 and table 12 show the comparison between the estimated turbidity of the sample for concept 2 and 3 respectively, compared to the industry standard measurement.

**Concept 2 Turbidity estimate**

| | Sample 1 | Sample 2 | Sample 3 |
|---|---|---|---|
| **IR** | 112.0314 | 84.67016 | 41.6911 |
| **Concept 2 NTU** | 65.72494 | 48.76618 | 22.12737 |
| **Lovibond TB 211IR NTU** | 65.2 | 32.5 | 22.5 |
| **Difference NTU** | 0.524937 | 16.26618 | -0.37263 |

*Table 11: Concept 2 Unknown Samples Turbidity Measurement*

**Concept 3 Turbidity estimate**

| | Sample 1 | Sample 2 | Sample 3 |
|---|---|---|---|
| **IR** | 27.59162 | 23 | 10.00524 |
| **Concept 3 NTU** | 90.19914 | 73.55076 | 26.43414 |
| **Lovibond TB 211IR NTU** | 65.2 | 32.5 | 22.5 |
| **Difference NTU** | 24.999 | 41.05075 | 3.934139 |

*Table 12: Concept 3 Unknown Samples Turbidity Measurement*

Each of the prototypes tested failed to give an accurate measurement of turbidity of unknown samples. The average difference between the perdicted NTU compared to the NTU measured using the industry standard for concept 2 and concept 3 is 5.47 NTU, and 23.33 NTU respectively.

Figure 34 and 35 show a graphical representation of the difference between concept 2 and 3, compared to the industry standard Lovibond TB 211IR.

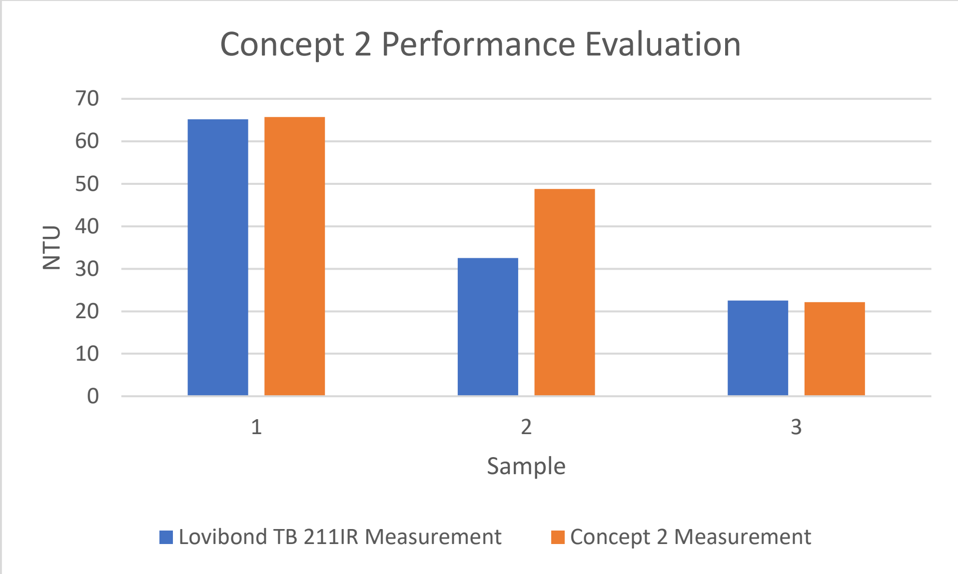

*Figure 34: Concept 2 Performance Evaluation*

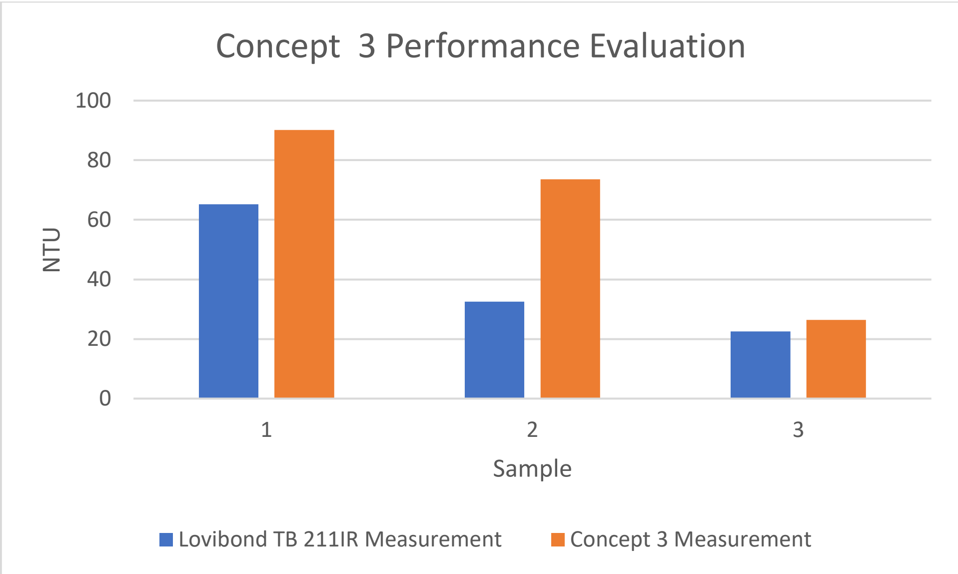

*Figure 35: Concept 3 Performance Evaluation*

Concept 2 significantly outpreformed concept 3, and accurately perdicted the turbidity of sample 1 and 3 however, concept 2 cannot consistently measure the trbidity of unknown samples of water and therefore is unreliable.

The readings from concept 2 and 3 did not accurately match the readings of the industry standard system. A reason for this could be the fact that the concepts measured the entire 150ml water sample, whereas the Lovibond TB 211IR uses a 10ml quartz crystal for its measurement, therefore only a small portion of the entire sample was measured using the industry standard. As in statistics, one cannot assume that a small sample, is an accurate representation of the entire population. Thus, one cannot assume that the turbidity of the 10ml sample reflects the turbidity of the entire 150ml sample. Therefore, the final concept was developed, such that it eliminates this factor.

### 7.4.2 Evaluation of Concept 4 – Cuvette Design

Each cuvette sample that was tested using the final concept, was also measured 3 times with the industry standard Lovibond TB 211IR. The average of those three measurements was taken as the NTU of that sample.

**Lovibond TB 211IR Measurements**

| | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 | Sample 6 |
|---|---|---|---|---|---|---|
| **Measurement 1** | 0.91 | 36.1 | 35.6 | 8.3 | 12 | 42.9 |
| **Measurement 2** | 1.02 | 35 | 32.6 | 9.4 | 12.4 | 46.8 |
| **Measurement 3** | 1.13 | 34.3 | 33.8 | 7.6 | 12.9 | 46.3 |
| **Average (NTU)** | **1.02** | **35.13** | **34** | **8.43** | **12.43** | **45.33** |

*Table 13:: Lovibond TB 211IR turbidity measurements of each sample*

Using the equation defined in chapter 6.3.3, and the measured infrared scattering intensity presented in section 7.2.4, table 14 shows the turbidity measurements using concept 4.

**Concept 4 Turbidity Measurement**

| | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 | Sample 6 |
|---|---|---|---|---|---|---|
| **Concept 4 (NTU)** | 0.51 | 33.55 | 31.42 | 7.31 | 10.06 | 43.79 |

*Table 14: Concept 4 Turbidity Measurements*

Figure 36 shows a comparison between the industry standard Lovibond TB 211IR system in blue, and the low cost final system in orange. Table 29 shows the difference between the two systems.

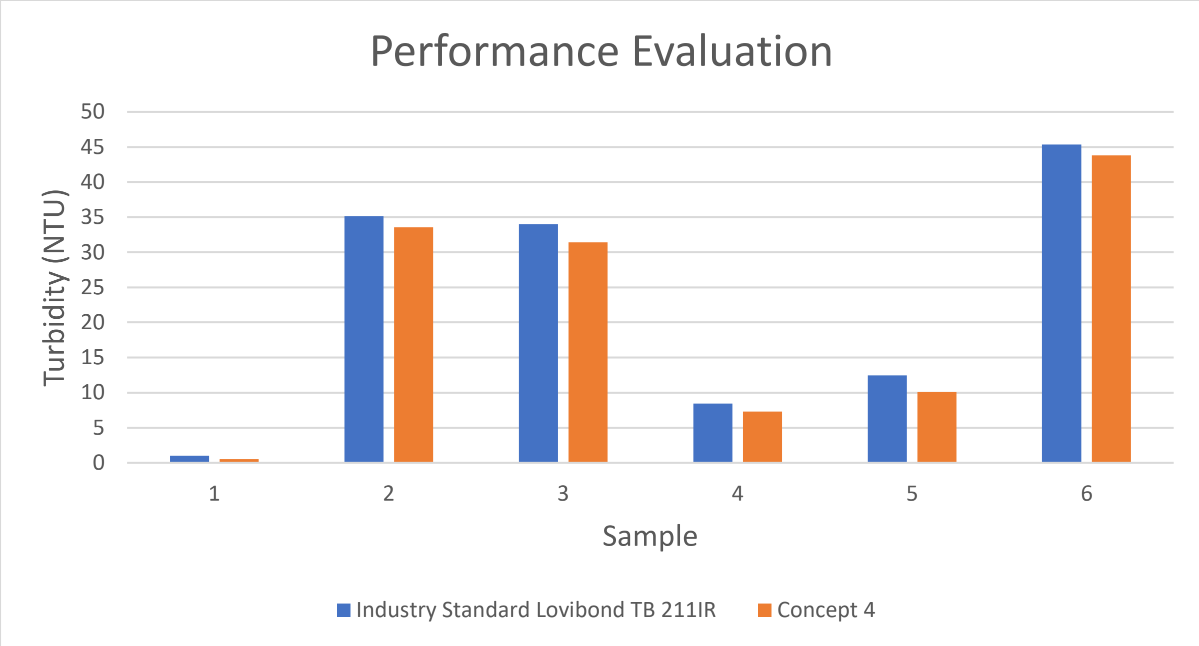


*Figure 36: Bar chart showing the comparison between the readings of the Lovibond TB 211IR and Concept 4*

| | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 | Sample 6 |
|---|---|---|---|---|---|---|
| **Concept 4 (NTU)** | 0.5128872 | 33.5249964 | 31.4148672 | 7.30675782 | 10.0620369 | 43.7914969 |
| **Lovibond TB 211IR (NTU)** | 1.02 | 35.1333333 | 34 | 8.43333333 | 12.4333333 | 45.3333333 |
| **% Difference (NTU)** | 0.5028305 | 0.95422191 | 0.92396668 | 0.86641397 | 0.8092791 | 0.9659889 |

*Table 15: Concept 4 vs Lovibond TB 211IR difference*

As can be seen, the results are very similar, with an average error of just 1.62 NTU, between the two systems for the six samples tested. Concept 4, can measure turbidity with an average of 84% accuracy, when compared to the industry standard Lovibond TB 211IR. There is however, a difference between the two results, with the final concept predicting a slightly lower value for the turbidity when compared to the industry standard. This difference is however systematic, as for each sample, the final concept predicted a slightly lower turbidity, meaning that with additional calibration, that error can be accounted for and eliminated, making the final system even more accurate.

# Chapter 8 – Discussion & Conclusion

The quantification of water turbidity is important for the monitoring of the proper working of the NX Filtration's nano membrane filtering system. While there exist systems industry standard for water quality analysis, they come at a great cost of above 1000 euros. This not only makes water quality analysis very expensive, but also inaccessible in developing countries, where measuring the quality of drinking water is especially important due to the low water quality standards in those countries. Therefore, the research question formulated at the start of the thesis was: *"How to develop a spectroscopy-based rainwater turbidity measurement system using low-cost components?"*

Together with the relevant stakeholders, it was decided that the goal of this graduation project was to develop a proof of concept, for a spectroscopy based low-cost nano particle turbidity measurement system. In total, three prototypes were developed and tested, and based on the evaluation of the, one final concept was developed. That final concept was calibrated using three control samples of turbid water, and then tested using six samples of water of unknown turbidity, with the goal of being able to accurately determine the turbidity of those samples. The final system was then evaluated, this was done by comparing the turbidity measurements of the six samples done by final system, to the turbidity measurements of the exact same samples done by the industry standard Lovibond TB 211IR. The final concept yielded measurements that very closely matched the measurements of the industry standard, with an accuracy of 84% relative to the Lovibond TB 211IR.

In conclusion, all the high priority stakeholder requirements were met, and the goal of developing a proof of concept for a low cost turbidity measurement system has been achieved. The results prove that the low-cost system can provide accurate measurements of turbidity, thus also answering the research question.

# Chapter 9 – Future Work

Improve current system with a cover for the top, such that it limits the amount of interference on the readings caused by the ambient light. This will probably further increase the accuracy of the system, and improve the usability, as measurements will not need to be performed in the dark. In addition, the current system can be further expanded to measure other parameters of water quality such as TDS, PH, concentration of benzene components, etc. This will allow for the WQI (water quality index) to be determined, thus allowing for a concrete quantification of the quality of the water tested. Additionally, the design of the current system could be changed, from a static measurement to an inline measurement system. This will allow for the system to continuously measure the quality of flowing water, and provide live readings. Finally, once all abovementioned improvements are implemented, the system should be designed in such a way that it can be installed on the SRB35K.

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# Appendix 1 – Arduino Code

```
#include <Wire.h>
#include "TSL2561.h"

// Example for demonstrating the TSL2561 library - public domain!

// connect SCL to analog 5
// connect SDA to analog 4
// connect VDD to 3.3V DC
// connect GROUND to common ground
// ADDR can be connected to ground, or vdd or left floating to change the i2c address

// The address will be different depending on whether you let
// the ADDR pin float (addr 0x39), or tie it to ground or vcc. In those cases
// use TSL2561_ADDR_LOW (0x29) or TSL2561_ADDR_HIGH (0x49) respectively
TSL2561 tsl(TSL2561_ADDR_FLOAT);

void setup(void) {
  Serial.begin(9600);

  if (tsl.begin()) {
    Serial.println("Found sensor");
  } else {
    Serial.println("No sensor?");
    while (1);
  }

  // You can change the gain on the fly, to adapt to brighter/dimmer light situations
  //tsl.setGain(TSL2561_GAIN_0X);         // set no gain (for bright situtations)
  tsl.setGain(TSL2561_GAIN_16X);      // set 16x gain (for dim situations)

  // Changing the integration time gives you a longer time over which to sense light
  // longer timelines are slower, but are good in very low light situtations!
  tsl.setTiming(TSL2561_INTEGRATIONTIME_13MS);  // shortest integration time (bright
light)
  //tsl.setTiming(TSL2561_INTEGRATIONTIME_101MS);  // medium integration time
(medium light)
  //tsl.setTiming(TSL2561_INTEGRATIONTIME_402MS);  // longest integration time (dim
light)

  // Now we're ready to get readings!
}

void loop(void) {
  // Simple data read example. Just read the infrared, fullspecrtrum diode
  // or 'visible' (difference between the two) channels.
  // This can take 13-402 milliseconds! Uncomment whichever of the following you want to
read
  uint16_t x = tsl.getLuminosity(TSL2561_VISIBLE);
  //uint16_t x = tsl.getLuminosity(TSL2561_FULLSPECTRUM);
  //uint16_t x = tsl.getLuminosity(TSL2561_INFRARED);
```

```
//  Serial.println(x, DEC);

  // More advanced data read example. Read 32 bits with top 16 bits IR, bottom 16 bits full
spectrum
  // That way you can do whatever math and comparisons you want!
  uint32_t lum = tsl.getFullLuminosity();
  uint16_t ir, full;
  ir = lum >> 16;
  full = lum & 0xFFFF;
  Serial.print("IR: "); Serial.print(ir);   Serial.print("\t\t");
  Serial.print("Full: "); Serial.print(full);   Serial.print("\t");
  Serial.print("Visible: "); Serial.print(full - ir);   Serial.print("\t");

  Serial.print("Lux: "); Serial.println(tsl.calculateLux(full, ir));

  delay(100);
}
```

# Appendix 2 – Raw Data

| Concept 1 – White casing IR readings | | | | | Concept 2 – Black casing IR readings | | | |
|---|---|---|---|---|---|---|---|---|
| Empty | 1 NTU | 13.5 NTU | 42 NTU | | Empty | 1 NTU | 13.5 NTU | 82 NTU |
| 1983 | 1034 | 1074 | 1120 | | 60 | 14 | 21 | 78 |
| 1983 | 1034 | 1074 | 1119 | | 60 | 14 | 21 | 78 |
| 1983 | 1034 | 1074 | 1121 | | 60 | 13 | 21 | 78 |
| 1983 | 1034 | 1074 | 1120 | | 60 | 13 | 21 | 78 |
| 1983 | 1034 | 1073 | 1120 | | 60 | 14 | 21 | 78 |
| 1983 | 1034 | 1073 | 1121 | | 60 | 14 | 21 | 78 |
| 1983 | 1034 | 1073 | 1122 | | 60 | 14 | 21 | 77 |
| 1983 | 1034 | 1073 | 1123 | | 60 | 14 | 21 | 77 |
| 1983 | 1035 | 1073 | 1123 | | 60 | 14 | 21 | 77 |
| 1983 | 1035 | 1073 | 1123 | | 60 | 13 | 21 | 77 |
| 1983 | 1035 | 1073 | 1123 | | 60 | 13 | 21 | 77 |
| 1982 | 1035 | 1074 | 1123 | | 60 | 13 | 21 | 77 |
| 1982 | 1035 | 1074 | 1123 | | 60 | 13 | 21 | 77 |
| 1982 | 1035 | 1074 | 1123 | | 60 | 13 | 21 | 77 |
| 1982 | 1034 | 1074 | 1124 | | 60 | 13 | 21 | 77 |
| 1982 | 1034 | 1074 | 1124 | | 60 | 13 | 21 | 78 |
| 1982 | 1034 | 1074 | 1124 | | 60 | 13 | 21 | 77 |
| 1982 | 1034 | 1074 | 1124 | | 60 | 14 | 21 | 77 |
| 1982 | 1034 | 1074 | 1124 | | 60 | 14 | 21 | 77 |
| 1982 | 1031 | 1073 | 1125 | | 60 | 14 | 21 | 77 |
| 1982 | 1032 | 1074 | 1124 | | 60 | 14 | 21 | 77 |
| 1982 | 1032 | 1074 | 1124 | | 60 | 13 | 21 | 77 |
| 1982 | 1032 | 1074 | 1123 | | 60 | 13 | 21 | 77 |
| 1982 | 1032 | 1074 | 1123 | | 60 | 13 | 21 | 77 |
| 1982 | 1032 | 1074 | 1123 | | 60 | 13 | 21 | 78 |
| 1982 | 1032 | 1074 | 1122 | | 60 | 13 | 21 | 78 |
| 1982 | 1032 | 1074 | 1123 | | 60 | 13 | 21 | 78 |
| 1982 | 1032 | 1074 | 1123 | | 60 | 13 | 21 | 78 |
| 1982 | 1032 | 1074 | 1123 | | 60 | 13 | 20 | 78 |
| 1982 | 1032 | 1074 | 1123 | | 60 | 13 | 20 | 78 |
| 1982 | 1032 | 1074 | 1124 | | 60 | 13 | 20 | 78 |
| 1982 | 1032 | 1074 | 1125 | | 60 | 13 | 20 | 78 |
| 1982 | 1032 | 1074 | 1125 | | 60 | 13 | 20 | 78 |
| 1982 | 1032 | 1074 | 1126 | | 60 | 13 | 20 | 78 |
| 1982 | 1032 | 1074 | 1126 | | 60 | 13 | 20 | 78 |
| 1982 | 1032 | 1074 | 1126 | | 60 | 13 | 20 | 77 |
| 1982 | 1032 | 1074 | 1126 | | 60 | 13 | 20 | 78 |
| 1982 | 1032 | 1074 | 1126 | | 60 | 13 | 20 | 78 |
| 1982 | 1032 | 1074 | 1126 | | 60 | 13 | 20 | 78 |

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| 1982 | 1032 | 1074 | 1125 | | 60 | 13 | 20 | 78 |
| 1982 | 1032 | 1074 | 1125 | | 60 | 13 | 20 | 78 |
| 1981 | 1033 | 1074 | 1124 | | 60 | 13 | 20 | 78 |
| 1981 | 1032 | 1074 | 1124 | | 60 | 13 | 20 | 78 |
| 1937 | 1033 | 1074 | 1124 | | 60 | 13 | 20 | 78 |
| 1981 | 1033 | 1074 | 1125 | | 60 | 13 | 20 | 78 |
| 1981 | 1032 | 1074 | 1125 | | 60 | 13 | 20 | 78 |
| 1980 | 1032 | 1074 | 1124 | | 60 | 13 | 20 | 78 |
| 1980 | 1032 | 1074 | 1124 | | 60 | 13 | 20 | 78 |
| 1981 | 1032 | 1074 | 1124 | | 60 | 13 | 20 | 78 |
| 1981 | 1032 | 1074 | 1124 | | 60 | 13 | 20 | 78 |
| 1981 | 1032 | 1074 | 1124 | | 60 | 13 | 20 | 79 |
| 1981 | 1032 | 1075 | 1123 | | 60 | 13 | 20 | 79 |
| 1981 | 1032 | 1075 | 1123 | | 60 | 13 | 20 | 79 |
| 1981 | 1032 | 1075 | 1123 | | 60 | 13 | 20 | 78 |
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| 1981 | 1033 | 1075 | 1123 | | 60 | 13 | 20 | 78 |
| 1981 | 1033 | 1075 | 1123 | | 60 | 13 | 20 | 78 |
| 1981 | 1033 | 1075 | 1123 | | 60 | 13 | 20 | 78 |
| 1981 | 1033 | 1075 | 1124 | | 60 | 13 | 20 | 78 |
| 1981 | 1033 | 1075 | 1124 | | 60 | 13 | 20 | 78 |
| 1981 | 1031 | 1075 | 1124 | | 60 | 13 | 20 | 78 |
| 1981 | 1032 | 1075 | 1124 | | 60 | 13 | 20 | 78 |
| 1981 | 1032 | 1075 | 1125 | | 60 | 13 | 20 | 78 |
| 1981 | 1033 | 1075 | 1125 | | 60 | 13 | 20 | 78 |
| 1981 | 1033 | 1075 | 1125 | | 60 | 13 | 20 | 78 |
| 1981 | 1033 | 1075 | 1125 | | 60 | 13 | 20 | 78 |
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| 1981 | 1033 | 1075 | 1125 | | 60 | 13 | 20 | 78 |
| 1981 | 1033 | 1075 | 1124 | | 60 | 13 | 20 | 78 |
| 1981 | 1033 | 1075 | 1125 | | 60 | 13 | 20 | 78 |
| 1981 | 1033 | 1075 | 1125 | | 60 | 13 | 21 | 78 |
| 1981 | 1033 | 1075 | 1125 | | 60 | 13 | 21 | 78 |
| 1981 | 1033 | 1075 | 1125 | | 60 | 13 | 21 | 78 |
| 1981 | 1033 | 1075 | 1126 | | 60 | 13 | 21 | 78 |
| 1981 | 1033 | 1075 | 1125 | | 60 | 13 | 21 | 78 |
| 1981 | 1033 | 1075 | 1126 | | 60 | 13 | 21 | 78 |
| 1981 | 1033 | 1075 | 1126 | | 60 | 13 | 21 | 78 |
| 1981 | 1033 | 1075 | 1126 | | 60 | 13 | 21 | 78 |

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| 1981 | 1033 | 1074 | 1126 | | 60 | 13 | 21 | 78 |
| 1981 | 1033 | 1074 | 1126 | | 60 | 13 | 21 | 78 |
| 1981 | 1033 | 1074 | 1127 | | 60 | 13 | 21 | 78 |
| 1981 | 1033 | 1074 | 1127 | | 60 | 13 | 21 | 78 |
| 1980 | 1033 | 1074 | 1127 | | 60 | 13 | 21 | 78 |
| 1981 | 1033 | 1074 | 1127 | | 60 | 13 | 21 | 78 |
| 1981 | 1033 | 1074 | 1127 | | 60 | 13 | 21 | 78 |
| 1981 | 1033 | 1074 | 1126 | | 60 | 13 | 21 | 78 |
| 1980 | 1033 | 1074 | 1126 | | 60 | 13 | 21 | 78 |
| 1980 | 1033 | 1075 | 1126 | | 60 | 13 | 21 | 78 |
| 1980 | 1033 | 1075 | 1126 | | 60 | 13 | 21 | 78 |
| 1980 | 1033 | 1075 | 1126 | | 60 | 13 | 21 | 78 |
| 1980 | 1033 | 1075 | 1126 | | 60 | 13 | 21 | 78 |
| 1980 | 1033 | 1075 | 1127 | | 60 | 13 | 21 | 78 |
| 1980 | 1033 | 1075 | 1127 | | 60 | 13 | 21 | 78 |
| 1980 | 1033 | 1075 | 1127 | | 60 | 13 | 21 | 78 |
| 1981 | 1033 | 1075 | 1127 | | 60 | 13 | 21 | 78 |
| 1981 | 1033 | 1075 | 1127 | | 60 | 13 | 21 | 78 |
| 1981 | 1033 | 1075 | 1127 | | 60 | 13 | 21 | 78 |
| 1981 | 1033 | 1075 | 1126 | | 60 | 13 | 21 | 78 |
| 1981 | 1033 | 1075 | 1126 | | 60 | 13 | 21 | 78 |
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| 1980 | 1033 | 1074 | 1126 | | 60 | 13 | 21 | 77 |
| 1981 | 1033 | 1074 | 1126 | | 60 | 13 | 21 | 77 |
| 1980 | 1034 | 1074 | 1126 | | 60 | 13 | 21 | 77 |
| 1980 | 1033 | 1074 | 1125 | | 60 | 13 | 21 | 77 |
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| 1980 | 1032 | 1076 | 1125 | | 60 | 12 | 20 | 76 |
| 1980 | 1032 | 1075 | 1125 | | 60 | 12 | 20 | 76 |
| 1980 | 1032 | 1076 | 1125 | | 60 | 12 | 20 | 76 |
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| 1981 | 1033 | 1076 | 1124 | | 60 | 12 | 21 | 77 |
| 1981 | 1033 | 1076 | 1125 | | 60 | 12 | 21 | 77 |
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| 1981 | 1033 | 1077 | 1126 | | 60 | 12 | 20 | 77 |
| 1980 | 1033 | 1077 | 1126 | | 60 | 12 | 20 | 77 |
| 1980 | 1033 | 1077 | 1126 | | 60 | 12 | 20 | 77 |
| 1981 | 1033 | 1077 | 1127 | | 60 | 12 | 21 | 77 |
| 1981 | 1034 | 1077 | 1127 | | 60 | 12 | 21 | 78 |
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| **Concept 3 – Narrow Light Source IR Results** | | | |
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# Concept 2 and 3 unknown sample measurements

| Concept 2 | | | | Concept 3 | | |
|---|---|---|---|---|---|---|
| Sample 1 | Sample 2 | Sample 3 | | Sample 1 | Sample 2 | Sample 3 |
| IR | IR | IR | | IR | IR | IR |
| 120 | 85 | 45 | | 29 | 24 | 10 |
| 120 | 85 | 44 | | 29 | 24 | 10 |
| 120 | 85 | 44 | | 29 | 24 | 10 |

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| 119 | 85 | 45 | | 29 | 24 | 10 |
| 119 | 85 | 45 | | 29 | 24 | 10 |
| 119 | 85 | 44 | | 29 | 24 | 10 |
| 119 | 84 | 44 | | 29 | 24 | 10 |
| 119 | 84 | 44 | | 29 | 24 | 10 |
| 120 | 83 | 45 | | 29 | 24 | 10 |
| 120 | 83 | 45 | | 29 | 24 | 10 |
| 120 | 83 | 44 | | 29 | 24 | 10 |
| 120 | 83 | 45 | | 29 | 24 | 10 |
| 120 | 83 | 45 | | 28 | 24 | 10 |
| 119 | 83 | 45 | | 28 | 24 | 10 |
| 119 | 83 | 45 | | 29 | 24 | 10 |
| 118 | 84 | 45 | | 29 | 24 | 10 |
| 118 | 84 | 45 | | 29 | 24 | 10 |
| 118 | 85 | 44 | | 29 | 24 | 10 |
| 118 | 85 | 44 | | 29 | 23 | 10 |
| 117 | 85 | 44 | | 29 | 23 | 10 |
| 117 | 86 | 44 | | 29 | 23 | 10 |
| 117 | 86 | 43 | | 29 | 23 | 10 |
| 117 | 86 | 43 | | 29 | 23 | 10 |
| 117 | 87 | 44 | | 29 | 23 | 10 |
| 118 | 87 | 44 | | 29 | 23 | 10 |
| 117 | 87 | 44 | | 29 | 23 | 10 |
| 114 | 87 | 43 | | 29 | 23 | 10 |
| 114 | 87 | 43 | | 29 | 23 | 10 |
| 117 | 87 | 43 | | 29 | 23 | 10 |
| 118 | 87 | 43 | | 29 | 23 | 10 |
| 118 | 87 | 43 | | 29 | 23 | 10 |
| 118 | 87 | 43 | | 29 | 23 | 10 |
| 117 | 87 | 42 | | 29 | 23 | 10 |
| 117 | 87 | 42 | | 29 | 23 | 10 |
| 117 | 87 | 43 | | 29 | 23 | 10 |
| 116 | 87 | 43 | | 29 | 23 | 10 |
| 116 | 87 | 43 | | 29 | 23 | 10 |
| 116 | 87 | 43 | | 29 | 23 | 10 |
| 116 | 87 | 43 | | 28 | 23 | 10 |
| 115 | 87 | 43 | | 28 | 23 | 10 |
| 115 | 87 | 43 | | 28 | 23 | 10 |
| 115 | 87 | 43 | | 28 | 23 | 10 |
| 115 | 87 | 43 | | 28 | 23 | 10 |
| 115 | 87 | 43 | | 28 | 23 | 10 |
| 115 | 87 | 43 | | 28 | 23 | 10 |
| 114 | 87 | 44 | | 28 | 23 | 10 |
| 114 | 87 | 43 | | 28 | 23 | 10 |
| 114 | 87 | 43 | | 28 | 23 | 10 |
| 114 | 87 | 43 | | 28 | 23 | 10 |

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| 114 | 87 | 43 | | 28 | 23 | 10 |
| 113 | 87 | 42 | | 28 | 23 | 10 |
| 113 | 87 | 42 | | 28 | 23 | 10 |
| 113 | 87 | 42 | | 28 | 23 | 10 |
| 113 | 87 | 42 | | 28 | 23 | 10 |
| 113 | 87 | 42 | | 28 | 23 | 10 |
| 113 | 87 | 42 | | 28 | 23 | 10 |
| 113 | 87 | 42 | | 28 | 23 | 11 |
| 112 | 87 | 42 | | 28 | 23 | 10 |
| 113 | 87 | 42 | | 28 | 23 | 10 |
| 112 | 87 | 42 | | 28 | 23 | 10 |
| 112 | 87 | 42 | | 28 | 23 | 10 |
| 112 | 87 | 43 | | 27 | 23 | 10 |
| 112 | 87 | 43 | | 27 | 23 | 10 |
| 112 | 88 | 43 | | 27 | 22 | 10 |
| 111 | 88 | 42 | | 27 | 23 | 10 |
| 111 | 88 | 42 | | 27 | 22 | 10 |
| 111 | 88 | 43 | | 27 | 22 | 10 |
| 111 | 87 | 42 | | 27 | 22 | 10 |
| 111 | 87 | 42 | | 27 | 22 | 10 |
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| 111 | 87 | 43 | | 27 | 22 | 10 |
| 111 | 87 | 43 | | 27 | 22 | 10 |
| 111 | 86 | 42 | | 27 | 22 | 10 |
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| 111 | 86 | 42 | | 27 | 22 | 10 |
| 111 | 86 | 42 | | 27 | 23 | 10 |
| 111 | 86 | 43 | | 27 | 23 | 10 |
| 111 | 85 | 43 | | 27 | 23 | 10 |
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| 111 | 85 | 42 | | 27 | 23 | 10 |
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| 112 | 85 | 42 | | 27 | 23 | 10 |
| 112 | 85 | 42 | | 27 | 23 | 10 |
| 112 | 85 | 42 | | 27 | 23 | 10 |
| 112 | 85 | 42 | | 27 | 23 | 10 |
| 112 | 85 | 42 | | 27 | 23 | 10 |
| 112 | 85 | 41 | | 27 | 23 | 10 |
| 111 | 85 | 42 | | 27 | 23 | 10 |
| 111 | 85 | 42 | | 27 | 23 | 10 |
| 110 | 85 | 42 | | 27 | 23 | 10 |
| 111 | 85 | 42 | | 27 | 23 | 10 |
| 111 | 85 | 42 | | 27 | 23 | 10 |
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| 111 | 85 | 42 | | 27 | 23 | 10 |
| 112 | 85 | 42 | | 27 | 23 | 10 |
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| 110 | 83 | 41 | | 28 | 23 | 10 |
| 110 | 83 | 41 | | 28 | 23 | 10 |
| 110 | 83 | 41 | | 28 | 23 | 10 |
| 110 | 83 | 41 | | 27 | 23 | 10 |
| 109 | 83 | 41 | | 27 | 23 | 10 |
| 109 | 83 | 41 | | 27 | 23 | 10 |
| 109 | 83 | 41 | | 28 | 23 | 10 |
| 109 | 83 | 41 | | 28 | 23 | 10 |
| 109 | 83 | 41 | | 27 | 23 | 10 |
| 109 | 84 | 41 | | 27 | 23 | 10 |
| 109 | 84 | 41 | | 27 | 23 | 10 |
| 109 | 84 | 41 | | 27 | 23 | 10 |
| 109 | 84 | 40 | | 27 | 23 | 10 |
| 108 | 84 | 40 | | 27 | 23 | 10 |
| 108 | 84 | 40 | | 27 | 23 | 10 |
| 109 | 83 | 40 | | 27 | 23 | 10 |
| 109 | 83 | 40 | | 27 | 23 | 10 |
| 109 | 83 | 40 | | 27 | 23 | 10 |
| 109 | 83 | 40 | | 27 | 23 | 10 |
| 109 | 83 | 40 | | 27 | 23 | 10 |
| 108 | 84 | 40 | | 27 | 23 | 10 |
| 108 | 83 | 40 | | 27 | 23 | 10 |
| 108 | 83 | 40 | | 27 | 23 | 10 |
| 108 | 83 | 40 | | 27 | 23 | 10 |

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| 108 | 84 | 40 | | 27 | 23 | 10 |
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| 108 | 83 | 40 | | 27 | 23 | 10 |
| 108 | 83 | 40 | | 27 | 23 | 10 |
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| 111 | 83 | 40 | | 27 | 22 | 10 |
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| 109 | 83 | 40 | | 27 | 23 | 10 |
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| 109 | 83 | 40 | | 27 | 23 | 10 |
| 109 | 83 | 40 | | 27 | 23 | 10 |
| 110 | 83 | 40 | | 27 | 23 | 10 |
| 110 | 83 | 40 | | 27 | 23 | 10 |
| 110 | 83 | 40 | | 27 | 23 | 10 |

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| 110 | 83 | 40 | | 27 | 23 | 10 |
| 111 | 83 | 40 | | 27 | 23 | 10 |
| 110 | 83 | 40 | | 27 | 23 | 10 |
| 110 | 83 | 40 | | 27 | 22 | 10 |

# Final Concept Raw Data

| CALIBRATION | | | | Unknown Sample Measurements | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| <0.1 NTU | 20 NTU | 200 NTU | | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 | Sample 6 |
| IR | IR | IR | | IR | IR | IR | IR | IR | IR |
| 71 | 125 | 514 | | 76 | 151 | 147 | 93 | 100 | 173 |
| 72 | 125 | 514 | | 77 | 151 | 146 | 93 | 101 | 174 |
| 73 | 125 | 514 | | 77 | 148 | 146 | 93 | 101 | 173 |
| 72 | 124 | 514 | | 78 | 148 | 145 | 93 | 101 | 173 |
| 72 | 124 | 514 | | 78 | 148 | 145 | 92 | 101 | 174 |
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| 72 | 124 | 514 | | 78 | 148 | 143 | 92 | 101 | 175 |
| 72 | 124 | 513 | | 77 | 150 | 145 | 93 | 100 | 176 |
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| 72 | 123 | 513 | | 76 | 149 | 147 | 92 | 99 | 173 |
| 72 | 123 | 513 | | 76 | 148 | 146 | 92 | 99 | 175 |
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| 72 | 123 | 513 | | 77 | 148 | 147 | 92 | 100 | 172 |
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| 72 | 123 | 513 | | 77 | 148 | 146 | 92 | 101 | 171 |
| 72 | 123 | 513 | | 76 | 150 | 146 | 92 | 100 | 172 |
| 72 | 123 | 513 | | 76 | 151 | 147 | 92 | 100 | 172 |
| 72 | 123 | 513 | | 76 | 150 | 147 | 92 | 99 | 173 |
| 72 | 123 | 513 | | 75 | 149 | 147 | 91 | 99 | 173 |
| 72 | 123 | 513 | | 76 | 148 | 147 | 91 | 98 | 173 |

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