Bachelor

Steffan Johan Kirk
Student number: 20130635

Undervisere:

Institute for Physics and Astronomy, Aarhus University

15. June 2016

Indhold

1

Background

1.1 Observations in space

Observations of objects in space can be conducted both from Earth and from orbits in space. Performing astronomy from Earth is however limited by the filtering and distortion of electromagnetic radiation caused by the Earth's atmosphere, a feature that protects life on Earth from ultraviolet and gamma rays. The altitude needed to detect the different bands of the electromagnetic spectrum is illustrated in figure 1.1. From Earth radio waves, near-infrared and visible light are observable. For observing other frequencies of the electromagnetic spectrum it is necessary to have observatories in space where the atmosphere isn't present. There are several ways of observing and examining objects in space, the two most commonly used are *Photometry* and *Spectrophotometry.*

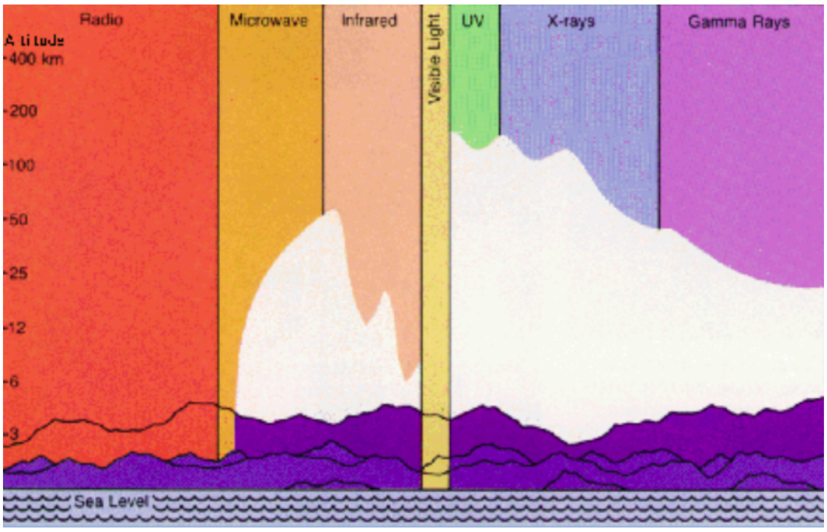


Figure 1.1: Illustration of the needed altitude to observe the different band of the electromagnetic spectrum.(Astronomy-Online)

1.1.1 Photometry

Photometry is concerned with measuring the intensity of an astronomical object's electromagnetic radiation. In its most basic form, photometry is conducted by gathering light through a telescope on to a photosensitive instrument which records the light energy, coming from the object being examined.

1.1.2 Spectrophotometry

1.2 The Space Mission Life Cycle and Architecture

When planning the work in space, a large amount of work must first be done back on earth. This is the case whether your are planning a manned mission or launching a satellite into orbit. Wertz and Larson (1999) gives a nice overview of the progress of designing a space mission:

- *Concept exploration*, The initial study phase, in which a broad definition of the space mission and its components.
- *Detailed development*, the formal design phase, which results in a detailed definition of the system components and test of hardware and development.
- *Production and deployment*, the construction of the ground and flight hardware and launch of the first full constellation of satellites.
- *Operations and support*, the day-to-day operations of the space system, its maintenance and support, and its deorbit or recovery at the end of the mission life.

Further more all space missions consist of a set of elements and the arrangement of these elements form the space mission architecture (Wertz and Larson, 1999).

The *subject* of the mission is the thing that interacts with or is sensed by payload. For the AU-SAT the subject is to observe the light from stars.

The *payload* consist of the hardware and software that sense or interact with the subject. The payload is contained within the *spacecraft bus* which also holds all the subsystems that handle, altitude, orbit, power, telemetry and data. The payload and spacecraft bus are together called the *spacecraft*. The payload for AUSAT mission would be the Cubesat itself, which include a telescope, an onboard computer, for communications and onboard data processing and likely a SPG to analyze the incoming light from the stars.

The *launch system* includes the launch facility and the launch vehicle that is needed to launch the payload into orbit.

The *orbit* is the path or trajectory of the spacecraft. There are several orbits the spacecraft enters before it reaches its mission orbit. The orbit can be an end-of-life orbit, where over time the spacecraft will be slowed down by drag and end up burning up in the atmosphere. The end-of-life orbit is usually used for Cubesats.

The *ground systems* consist of the ground stations that connect with the spacecraft, so the operators are able to control the spacecraft and receive the telemetry and the mission data.

For the AU-SAT the Department of Physics and Astronomy will decide the subject of the mission and determine the payload for the satellite. The scope of this bachelor's thesis is to examine a possible type of SPG that could be included in the payload if the satellite is launched. The spacecraft bus will be delivered by the Danish Cubesat company GomSpace. For the launch system, it will be required to buy a free spot on a commercial rocket, that would deliver the spacecraft on a desired orbit for observations.

2

Development and Setup of Physical Tests

2.0.1 Preface

In order to determine which mission objects would be possible with a spectrograph (SPG) similar to the USB4000, it was necessary to preform initial testing on the USB4000. To examine the USB4000 it was decided to develop different setups to test the stability of the measurements. In an orbit in space the SPG will be pointed at different objects to analyze the light they radiate and thereby analyze the properties of the objects.

In the laboratory however the light source observed by the SPG needed to be a light source with a very well known spectrum in the range of the USB4000. For a well know light source and its spectrum, the true wavelength of a peak located in the spectrum is well documented, which enables the SPG to be calibrated as precisely as allowed by the resolution of the SPG. Upon the development of the setups it was necessary to consider what kind of environment the SPG could be subject to if it was launch to space.

As mentioned in section REFERENCE OBSERVATIONS, two common factors when in an orbit, are vibrations and variations of the temperature inside the spacecraft. Furthermore the observations of astronomical objects are often performed over a long duration of time. With these factors taken in to consideration, three physical test (PT) setups with different purposes were designed,

1. Stationary Physical Test - Analysis of measurements with the USB4000 being stationary.

2. Simulated Vibration Physical Test - Analysis of measurements with the USB4000 being moved to simulated vibrations.

3. Temperature Dependence Physical Test - Analysis of measurements with the USB4000 at variable temperatures.

The development, purpose and improvements of the three PTs and the calibration of the USB4000 will be discussed in the following sections.

2.0.2 Calibration of the USB4000 Spectrograph

From Manual (Tuesday)

Helium Spectrum

To examine the stability of the USB4000 SPG, six spectral lines within the Helium spectrum will be used. Helium has well know spectral lines that are well defined and distributed across the wavelength reach of the USB4000 SPG being examined in this bachelor's thesis. The use of well defined spectral lines ensures that any broadening or shift of the spectral lines are happening within the SPG. In figure 2.1 (Born, 2014) the spectral lines in the Helium spectrum in the range 380-900 nm are shown.

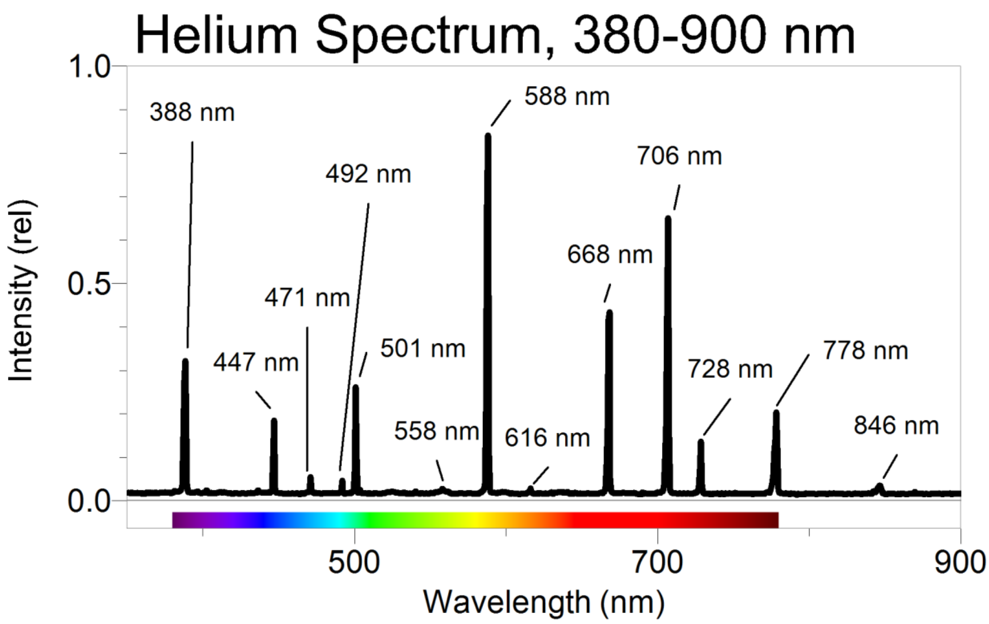


Figure 2.1: Spectral lines in the Helium spectrum in the range 380–900 nm (Born, 2014).

The wavelengths of the six peaks used in the experiments of this thesis can be seen in table 2.1 (Abramzon and Siegel, 1999).

2.0.3 First Physical Test- Stationary Measurements

The purpose of the first setup was to determine the stability of multiple readings over a long period of time from the USB4000. The parts used for the first initial setup were:

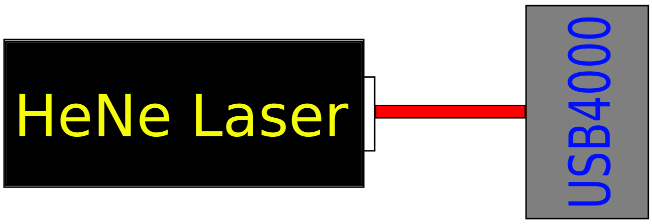
- HeNe laser
- USB4000 Spectrograph with the data acquisition software, *SpectraSuite*.

Peak number	Wavelength [nm]
1	388.9
2	447.1
3	501.6
4	587.6
5	667.8
6	706.5

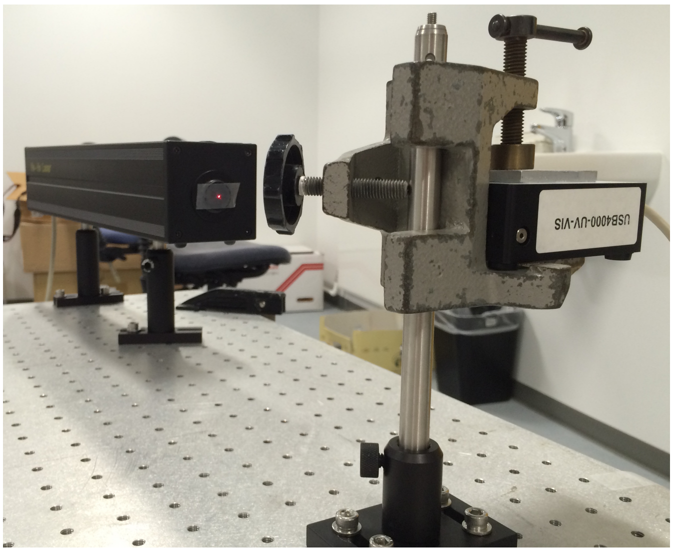
Table 2.1: Wavelengths for the six spectral lines that will used in the experiments of this thesis (Abramzon and Siegel, 1999).

- Optical bench for mounting the setup

The HeNe laser was chosen as the first light source because it had a well documented single peak in its spectrum, and we already had the laser in the Astro Lab. The initial setup for the first PT, is shown in figure 2.2, where a sketch of the setup is illustrated as well as a picture of the actual setup.



(a) Sketch of the setup for the first PT.



(b) Actual setup for the first PT.

Figure 2.2: The setup for the initial run of the stationary measurement with a HeNe laser as the light source. In 2.2a a sketch of the top view of the setup is illustrated and in figure 2.2b the actual setup is shown from an angle. The tape used as a collimator is visible over the output lens of the laser.

The setup for the stationary measurement was very simple as there were no moving parts or control of temperature as was done in later tests. For the execution of the PT the HeNe laser was aligned with the USB4000 which was connected to the data acquiring software, *SpectraSuite*. The laser was fitted with tape across the output lens, this was done because the tape performs like a collimator which causes the light beam to become more aligned in the same direction. This was done as an attempt to make the setup less sensitive to alignment of the laser dot on the entrance slit on the SUB4000. The parameters for the initial test were,

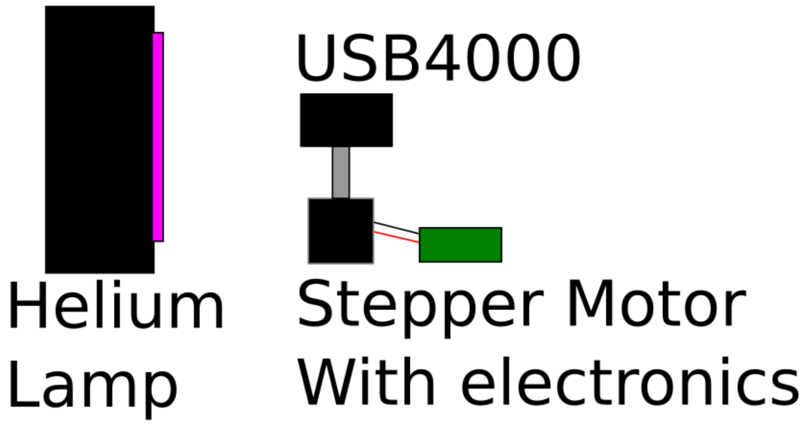
- The HeNe Laser was set to an output of 1 mW and tape was used as a collimator by placing it over the exit slit of the laser which was pointed onto the entrance slit of the USB4000.
- In *SpectraSuite* the integration time was set to 10 ms, allowing for a high peak to be located. Measurements were done every 20 s for a total of 1000 measurements.
- *SpectraSuite* saved the intensity for every wavelength to a text file, without any filtering of noise from the CCD and no averaging over wavelengths next to each other.

The data from the measurement was saved without any processing done by *SpectraSuite* because this was done in data processing later on where the methods of processing could be controlled. After the run of the initial setup some problems with the draft were found,

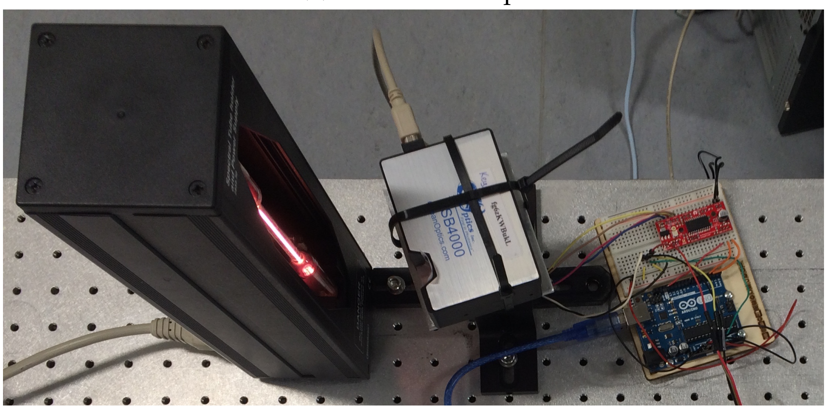
- The setup was very dependent on alignment of the laser and the USB4000. Small vibrations could cause observable changes in the alignment, that could cause the laser to saturate the CCD detector of the USB4000, making the measurements useless.
- The change in alignment was also able to change the form of the peak in the measured spectrum, which was most likely because of internal reflections within the USB4000.
- Although the HeNa laser produces a well defined peak, it would be preferable if several peaks located over the range of the USB4000 could be observed.

After running the initial setup where the problems mentioned earlier were present, improvements to the setups were introduced. Most of the issues were in someway related to the use of the HeNe laser as the light source. The size of the light spot from the laser was to small compared to the entrance slit of the USB4000, this meant that the light over the whole entrance slit was not as uniform as desired.

To address the problems of the initial setup ,the light source used for measurements was changed to the Helium lamp which was used for calibration as well. This meant that several peaks across the measurable range could be selected in the output spectrum to observe for the PTs and the light hitting the entrance slit would be more uniformly spread out. Furthermore the mounting to the optical bench was changed in such way that it could be used for the second test as well, which examined simulated vibrations of the USB4000. The USB4000 was therefore mounted on top of the shaft of a stepper motor. The stepper motor was mounted with four 90° angle pieces onto the optical bench next to the electronics controlling it. The stepper motor was turned off for the stationary test but could be made to move when needed in the second PT. A sketch and the real setup can be seen in figure 2.3.



(a) Sketch of setup.



(b) Actual setup.

Figure 2.3: The final setup for both the stationary PT and simulated vibration PT. Figure 2.3a shows a sketch of the setup seen from the side and figure 2.3b shows the actual setup. The electronics were only used to control the stepper motor in the simulated vibration PT.

The change of light source meant that the final parameters of the test were changed,

- The light source was changed to the Helium calibration lamp.
- The tape used as a collimator was moved to the entrance slit of the USB4000 and the Helium lamp was placed at a distance where the CCD detektor in

the USB4000 was not saturated.

- Integration time in *Spectrasuite* was set to 100 ms. Measurements were still done every 20 s for a total of 1000 measurements, and saved to a text file with the intensity for every wavelength for data processing.

2.0.4 Second Physical Test - Simulated Vibration

The purpose of the second physical test was to test the stability of the measurements from the USB4000, when it was exposed to vibrations. The setup for the second PT included the parts used for the final setup in the stationary PT but with a few variations,

- The stepper motor was now used to simulate vibrations by rotating the USB4000 back and forth over an angle spanning 45°. The rotation was done with a frequency of 1,04 Hz, which allowed for enough light exposure at the different angles for the USB4000 to obtain detectable peaks in the output spectrum.
- The electronics used to control the stepper motor were the two commercial development boards, *Raspberry Pi* and *Arduino Uno*. These were programmed to moved the stepper motor at the desired frequency.
- Measurements were taken every 20 s for a total of a 1000 measurements. Every measurement was saved to a text file, with the intensity for every wavelength.

The setup was the same as for the stationary measurement which can be seen in figure 2.3.

2.0.5 Third Physical Test - Temperature Dependence

The purpose of the third physical test was to determine the temperature dependency of the measurements from the USB4000. For this PT it was necessary to build a housing environment were the temperature could be controlled as precisely as possible. The system would need to be well insulated so the temperature inside could be kept stable for long enough time to allow the temperature of the USB4000 to come in to equilibrium with the set temperature. Furthermore a window for the light to enter the housing was preferable as this would allow the light source to be placed outside the housing, allowing for a smaller volume in which the temperature needed to be controlled. For the actual heating of the housing and how to control the temperature precisely, different methods were considered,

- A hot air blower manually set to different temperatures.
- Thermoelectric cooling by using a Peltier device, which can transfer heat from one side of the device to the other depending on the direction of the current going through it, thereby being able to heat up one of the device sides.

- A heater circuit design by ourselves and controlled by a PID controller.

For the use of a hot air blower the housing for the PT would quickly become complicated to build to allow for a hot air entrance without a large heat loss, which could cause the temperature to be unstable. A Peltier device is mainly used for cooling purposes by ensuring that the hot side of the device itself is cooled. Thereby allowing the cold side to be cooled even further by transferring its excess heat to the hot side. It would be to time consuming to develop a setup that worked with precision control of the hot side of the Peltier device.

Therefore a setup using a heater circuit we designed ourselves, that could keep the volume of the housing small and would only need a few wires to be run inside the housing, was decided on. The heater circuit was controlled by an *Arduino Uno* running PID controller software. After discussing with the electronics department of Aarhus University Institute for Physics and Astronomy, a simple circuit was designed which satisfied our needs. The circuit schematics can be seen in figure 2.4. The circuit is run of a 12 V power supply, with the positive terminal connected to a power resistor, functioning as the heating element of the circuit. The high power resistor is capable of having large amounts of power delivered to it, causing it to heat up as current flows through it and as the voltage drops across it. The resistor was connected to ground through a transistor controlled by the *Arduino Uno*. The transistor works as a switch, which connects the collector and emitter legs of the transistor when a voltage is applied to the base leg. The resistor was connected to the collector leg and the emitter leg was connected to ground, while the base leg was connected to the *Arduino Uno* with the PID software. The PID software controlled when and for how long the collector and emitter legs were connected based on the temperature readings from a temperature sensor connected to the *Arduino Uno* from inside the test housing. With the wanted temperature inside the housing being adjustable from the PID software, the test could be run without the need to physical interrupt the setup.

After deciding on the wanted setup, an initial test setup was build to ensure the heating circuit and PID controller were working as planned. The initial setup was constructed with the parts,

- The housing was made from a small cardboard box, as high insulation was not needed for testing if the heater circuit and PID controller worked as expected.
- A 12 V power supply, BD649 Transistor, SH650 Resistor and TMP35 Temperature sensor. The data-sheets of the components can be found in appendix A.

The USB4000 was placed in the housing where a window had been made for the light to enter. Tape was used to insulate the window and work as a collimator like in the previous PT's. The power resistor was mounted on a heatsink in contact with the USB4000, the temperature sensor was mounted on the USB4000

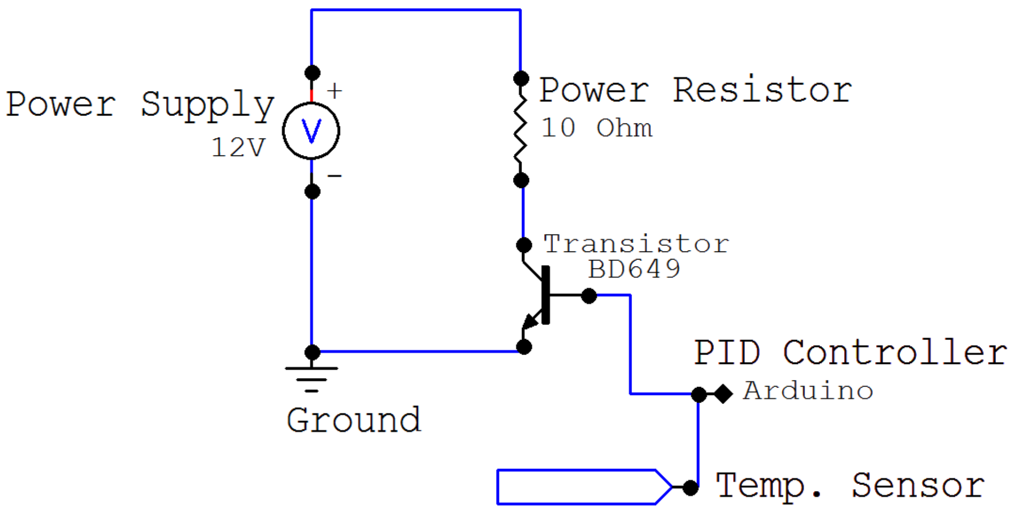
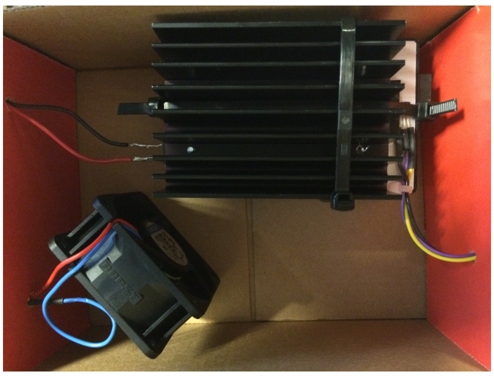
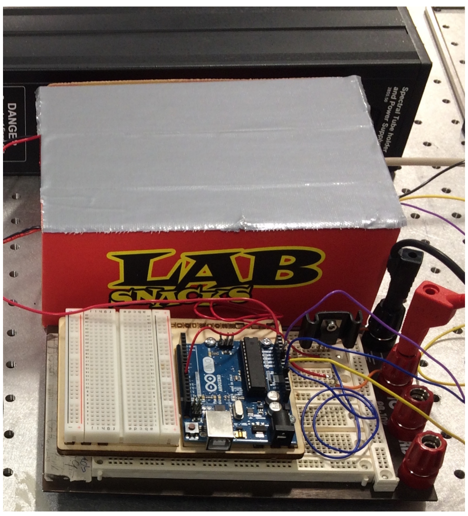


Figure 2.4: Schematic view of the heater circuit used to control the temperature in the housing for the temperature dependency PT.

as well. The power resistor and temperature sensor were mounted directly onto the USB4000 because it was expected to provide the fastest heating and most stable temperature readings. A small fan was put in the housing to circulate the air to get a uniform temperature inside the housing. The cables were then run outside the housing to the remaining circuit. The setup inside and outside the housing can be seen in figure 2.5.



(a) Inside of housing.



(b) Outside view of the circuit test.

Figure 2.5: The inside and outside view of the setup to test the heater circuit and PID controller. 2.5a shows the resistor with heatsink and the temperature sensor mounted on top of the USB4000 as well as the fan for circulating the air. In 2.5b the outside of the setup is shown, including the Helium lamp in the background, the part of the heater circuit located outside the housing.

After conducting the initial test of the heater circuit and PID controller some adjustments were made for the final setup to improve stability of the temperature in the housing,

- The housing was changed to a Styrofoam box for better insulation allowing the set temperature to be reached faster.
- The resistor and temperature sensor were moved so they were not in contact with USB4000, but instead the heating and temperature measurements were done on the circulating air. This was done because experience showed it allowed for a much stabler temperature within the housing.
- As the PID parameters are unique for every system, they were fine tuned for the Styrofoam housing.

The final setup for the third PT with the mentioned improvements can be seen in figure 2.6.

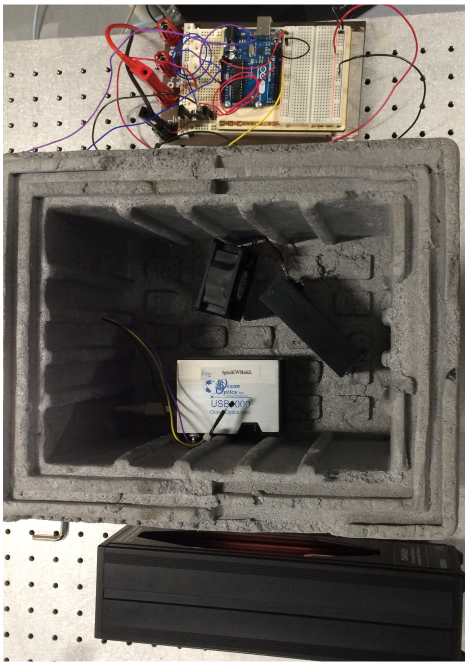


Figure 2.6: The final setup used for the third PT. The USB4000 was placed with the entrance slit aligned with the light window made in the side of the housing. The resistor with heatsink was placed in front of the fan so the circulating air was heated and the temperature sensor was placed so it measured the air temperature. The housing was closed of with a lid when the PT was run.

With the final setup decided upon the third PT was run with the parameters,

- Measurements were made with the temperature varying from 19,5° to 49,3° in eleven equally spaced steps. Because the USB4000 was heated by the circulating air, the temperature was hold steady for each step for two hours to allow for uniform temperature in the USB4000.

- Integration time in *SpectraSuite* was set to 100 ms and measurements were taken every 1 s for a total of 60 measurements for every temperature step. The intensity of every wavelength was saved to a text file for data processing.

3

Results

3.1 General method of data processing

The Helium spectrum from each measurement was saved to a text file, which included wavelengths with corresponding photon count. As an example of what the Helium spectrum from a measurement looks like, the unfiltered data with background noise, from a stationary measurement is shown in figure 3.1.

The six peaks that will be used for determining the stability of the SPG for all three experiments, are marked and numbered from one to six, with the numbering starting from the peak with the lowest wavelength. The data from all measurements within each experiment will firstly have the background noise from the CCD sensor removed. This is done by using the intensity for wavelengths below 350 nm, where no spectral line are present from Helium, here only the noise on the CCD sensor is present, the average of the measured intensity for all wavelengths below 350 nm is subtracted from the relative intensity for all data. Then for every measurement the six marked peaks in figure 3.2 will be found within each spectrum, and a Gaussian function will be fitted to each peak to determine the centroid location of all the peaks, and it is these centroid locations that will we compared within all three experiments. The general form of a Gaussian function is:

$$f(x) = A \cdot exp\left(-\frac{(x-b)^2}{2 \cdot \sigma^2}\right), \tag{3.1}$$

where, A is the peak value, b is the centroid value of the peak and σ is the standard deviation, which determines the width of the Gaussian profile.

The typical form of a peak with a fitted Gaussian function is shown in figure 3.2a. It can be seen that the peak has a "shoulder" on the right side. It is so because the peak is actually made up of two Gaussian functions that overlap, this is shown in figure 3.2b, where the two single Gaussian functions that make up the combined Gaussian function, are illustrated separately. From section 2.0.2 we know the spectral lines of Helium are well defined, this means that

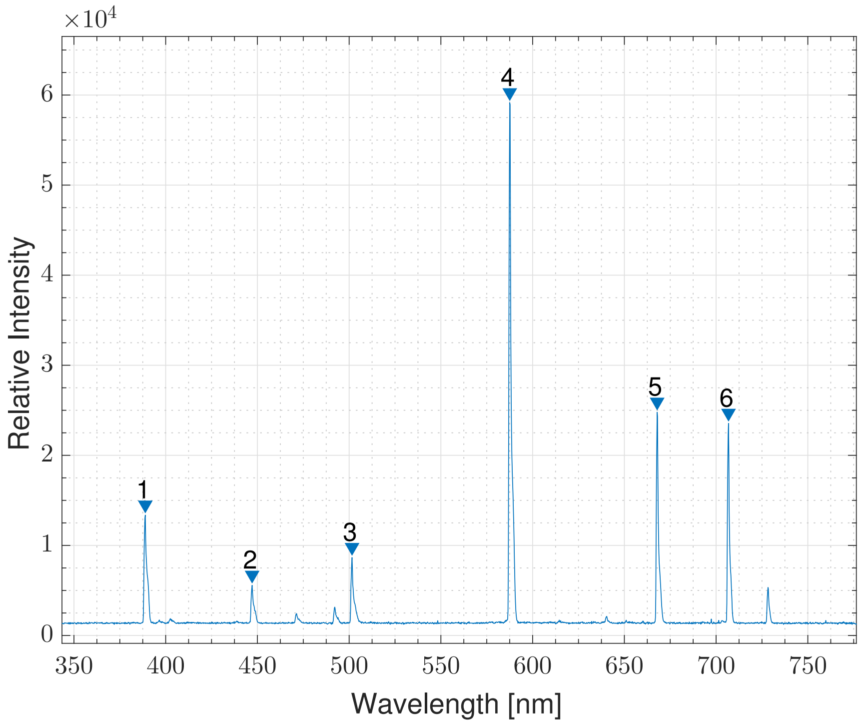


Figure 3.1: Example of the Helium spectrum from a measurement with the SPG, here illustrated by a spectrum from a stationary measurement. The six peaks that are used to determine the stability of the centroid location are marked and numbered one to six starting from the peak with the shortest wavelength.

the "shoulder" of the spectral line is caused by internal reflections within the USB4000 SPG. To determine the specific cause of the broadening, it would be necessary to take the USB4000 SPG apart and do further testing, this is beyond the scope of this bachelor's thesis but the broadening will be filtered out in the data processing.

This means that to accurately identify the centroid of the peak, in which we are interested, it is necessary to fit to a combination of two Gaussian functions of the form:

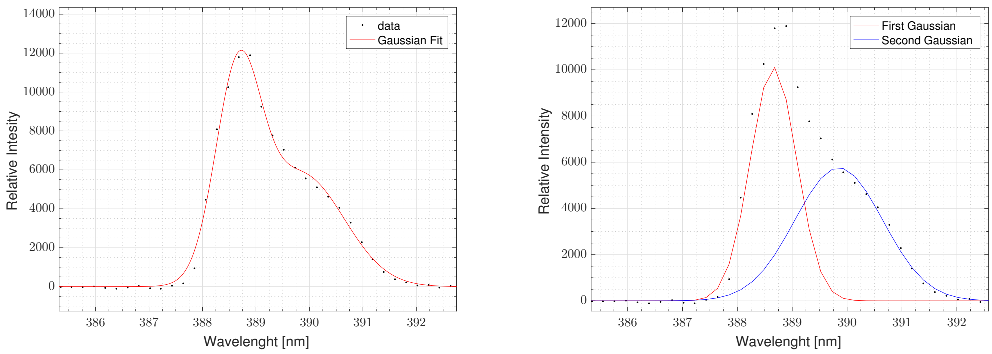
$$f(x) = A_1 \cdot exp\left(-\frac{(x-b_1)^2}{2\cdot\sigma_1^2}\right) + A_2 \cdot exp\left(-\frac{(x-b_2)^2}{2\cdot\sigma_2^2}\right), \tag{3.2}$$

and when a fit in the form of equation 3.2 has been found, we are able to get the information about the two separate Gaussian function and thereby get the centroid information about the narrow and tall peak in which we are interested.

The uncertainty for the centroid locations is the emphFull Width at Half Maximum (FWHM) which is determined by the standard deviation, σ. The relationship between the two is given by:

$$FWHM = 2\sqrt{2ln2}\sigma, \tag{3.3}$$

where σ is obtained from the Gaussian function fitted to every peak.



(a) Typical peak form, with double Gaussian fitted.

(b) The two single Gaussian functions that make up the fit in figure 3.2a.

Figure 3.2: Overview of the general observed Gaussian peak form. Figure **(a)** shows the form of the two combined Gaussian functions that are fitted to the experimental data and figure **(b)** shows how the combined Gaussian can be split up into two single Gaussian functions.

3.2 Stationary measurements

The first experiment which was designed to show the stability of the spectrum measurements of the SPG over time, ran for a thousand measurement, each measurement separated by a twenty seconds pause.

A

Herro

Bibliography

Nina Abramzon and P.B. Siegel. Introductory helium atomic spectrum analysis. *American Journal of Physics*, 77, 1999.

Astronomy-Online. Concepts - atmospheric limitations. URL http://astronomyonline.org/Science/AtmosphericLimitations.asp?Cate=Home&SubCate=MP01&SubCate2=MP020102.

Richard Born. A quantitative investigation of the helium spectrum. Technical report, Northern Illinois University, 2014.

James R. Wertz and Wiley J. Larson. *Space Mission Analysis and Design*. Springer Netherlands, 1999.